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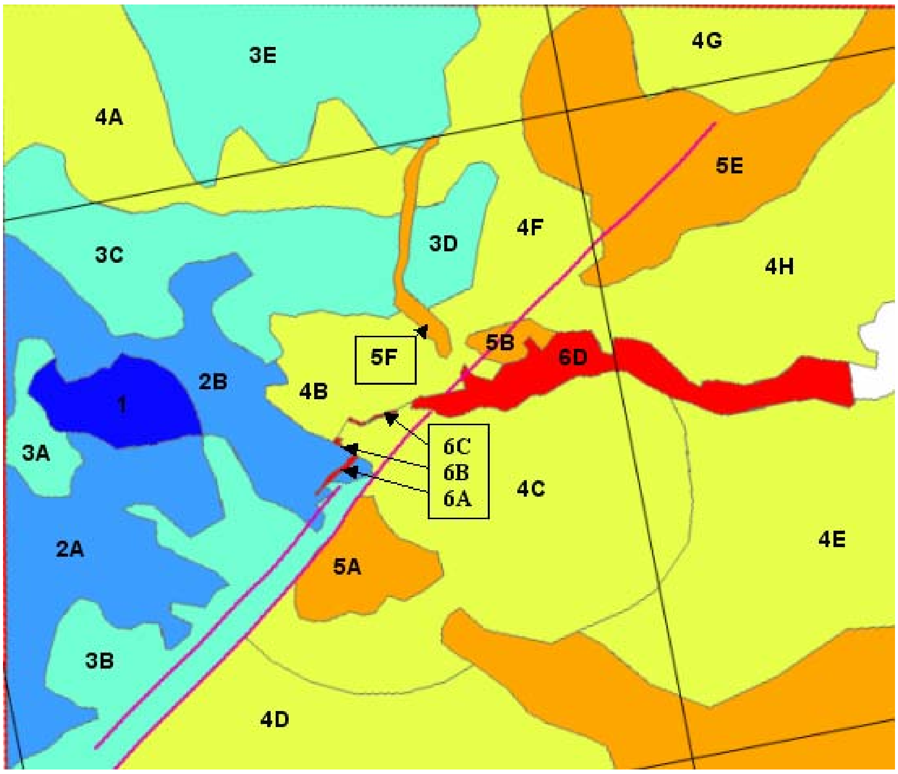
Absolute Fixing of Tide Gauge Benchmarks and Land Levels: the BGS contribution to a report on a study of the London and Thames estuary region

Geology and Landscape (Southern Britain) Programme

Confidential Commissioned Report CR/07/043N



BRITISH GEOLOGICAL SURVEY

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Absolute Fixing of Tide Gauge Benchmarks and Land Levels: the BGS contribution to a report on a study of the London and Thames estuary region

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Keywords

Land levels; uplift; subsidence; London; Thames estuary; GPS; PSI; compressible ground.

Front cover

Average ground velocity domains in the London area. Blue (rank 1) denotes uplift at about 0.3 mm/yr; red (rank 6) denotes most rapid subsidence, at about –2 mm/year. See Figure 3 and text for more details.

Bibliographical reference

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1 Introduction

This report comprises material submitted as the British Geological Survey (BGS) contribution to the final report of a project measuring changes in land and sea levels using high precision global positioning system (GPS) surveying, absolute gravimetry (AG), persistent scatterer interferometry (PSI) and tide gauge records. Data was collected during the period 1997 to 2005 for a National study of changes around the coast of Great Britain, and a Regional study of changes along parts of the Thames Estuary and the River Thames at London.

Since 2003, the national study has been funded by the Joint DEFRA/EA Flood and Coastal Erosion Risk Management R&D Programme, and a regional study, funded by the Environment Agency Thames Estuary 2100 project. The national study was carried out jointly by the Proudman Oceanographic Laboratory (POL) and the University of Nottingham's Institute of Engineering Surveying and Space Geodesy (IESSG). The regional study was led by IESSG and carried out jointly by IESSG, POL, Nigel Press Associates Ltd. (NPA) and the British Geological Survey (BGS).

The item in the project research plan relevant the main BGS input is Objective 08:

> 'The estimates of changes in absolute ground level for the regional network of 13 GPS stations and a few thousand PSI points (output from 07) will be analysed, and geological interpretations presented using the geological database and other available information'.

The final project report includes a condensed version of this material, with only a few of the figures. That is due to be published as Environment Agency R&D Technical Report FD2319/TR.

The geological setting of the London region is described in a report for the EA/NERC CONNECT B project (Bingley et al., 1999), and by Ellison et al. (2004).

2 The geology of the London region GPS stations and nearby PS points

This section describes the geology of each of the GPS station sites in the Thames regional study, and compares it with that of selected PSI points within a surrounding 400 m radius. It was largely prepared by DTA on 25 August 2006, with additional observations on the Thames Barrier dated 8 December 2006. It is based on an initial version dated 19 July 2006. It takes account of information and comments on that version provided by Richard Bingley (IESSG).

The following descriptions are derived by reference to current BGS 1:10 000 scale geological maps (except for Sheerness and Thurnham, where the 1:50 000 scale geological map was used), current OS 1:10 000 topographic maps, historic OS 1:10 560 topographic maps and (where relevant) local borehole records. The survey points were located relative to these datasets within a GIS. In some cases, large-scale aerial photography of the sites was also inspected.

The sites described are as marked on large-scale maps (mostly at 1:1250) supplied by Richard Bingley, 14 July 2006, supplemented by National Grid coordinates for GPS stations and PS points, also as supplied by Richard Bingley. It is noted that the PS points are georeferenced by NPA (Nigel Press Associates) to an accuracy only between 15 to 50 m. It is assumed that PS points relate to built structures within 50 m of their nominal location.

The assessments of possible differential ground movement within each sampling area were made without reference to the PSI data.

2.1 SUMMARY

There is a possibility of differential ground movement between the GPS station and some of the selected nearby PS points, due to local geological variation, at the following sites:

Barking Barrier:

Some possibility of differential movement of those PS points north of the GPS station.

Sheerness Docks:

Some possibility of differential movement between GPS station and PS points on deep-piled piers and structures around the Boat Basin, compared with nearby areas of artificial ground on alluvium.

Sunbury Yard:

PS points along Fordbridge Road and to the north-west are less susceptible to subsidence than the GPS station, and the PS points south-east of Fordbridge Road.

Gravesend Grammar School:

Differential subsidence between the larger buildings east of Church Walk and the smaller buildings west of Church Walk is a possibility.

Richmond:

Differential movement of one selected PS point, south of the south end of the Richmond Footbridge, seems possible.

Tower Pier:

Some differential movement between the GPS station and most of the PS points (excepting those immediately east of the GPS station) could occur. Differential movement between the tide gauge and the GPS site is also possible. A cluster of the selected PS points north-west of the GPS station appears to be associated with Tower Place, which was constructed during the period of InSAR data collection.

2.2 BARKING BARRIER (BARK)

The GPS station is on the West Tower of the Barrier. It is known that the Barrier towers are founded in bedrock, and that their foundations pass through the Thanet Sand Formation, which is at depths below ground level between about 10 m and 17.8 m, into the Chalk Group. The Thanet Sand is expected to be in hydraulic continuity with the Chalk. Both are below sea level and so can be expected to be permanently saturated.

The selected PS points lie in two areas, respectively to the south and north of Barking Creek.

It seems likely that those PS points south of the Creek relate to parts of the Barking Barrier, i.e. the West Tower and the control room. The control room was constructed on a narrow peninsula of post-1938 artificial ground, laid directly on the natural superficial deposits. The latter comprise alluvial deposits (including tidal river deposits) to a depth of about 4 to 5 m, overlying river terrace gravels, above the Thanet Sand and Chalk bedrock. Again it is known that the control room foundations pass through the alluvial deposits and the Thanet Sand into the Chalk. Hence, no significant differential settlement between the West Tower and the control room would be expected.

PS points north-east of the Barrier probably relate to single storey works buildings on a site with only thin artificial ground, if any. The geology is otherwise essentially similar to that of the Barrier control room but the alluvium is probably older, and may be somewhat thinner. Also, this site was first developed pre-1920, so it can be expected that most settlement due to compression of the alluvium occurred pre-1997. Thus little or no differential settlement, compared with the Barrier, would be expected.

PS points north of the Barrier probably relate to single storey works buildings on artificial ground laid post-1920, above alluvium and terrace gravels. The bedrock could be either Thanet Sand Formation (here thicker than at the Barrier) or the overlying Lambeth Group. However, it seems unlikely that the structures corresponding to the PS points are founded more than 10 m deep in bedrock. Indeed, they may be founded in artificial ground and so susceptible to compression of the underlying alluvium. The site was first developed pre-1938, so it can be expected that most settlement due to compression of the alluvium occurred pre-1997, unless further artificial ground was added to the site more recently. Therefore there is a possibility of greater differential settlement at these PS points, compared with the Barrier.

2.3 SHEERNESS DOCKS (SHEE)

The GPS station is adjacent to the tide gauge on a jetty close to the entrance to the Docks.

The area covered by the GPS and PS points is entirely underlain by the London Clay Formation, here presumed to lie permanently below sea level, and alluvium (including tidal river deposits). River terrace gravels probably occur beneath the alluvium. Local borehole records suggest that bedrock lies more than 20 m deep. It is presumed to be permanently saturated by water and so not to be liable to seasonal shrink-swell. Alluvium is the only formation present which is likely to be significantly compressible.

No artificial ground has been mapped in this vicinity by BGS, although some is likely to be present throughout the area. The Docks and surrounding area have been developed since 1930 at latest but modern redevelopment could change the pattern of ground loading, possibly leading to differential compression of the alluvium.

However, it is possible that the pier with the tide gauge, and perhaps also the area around the Boat Basin, have been built on piles. This would be expected to render them less susceptible to such differential compression of the alluvium.

2.4 SUNBURY YARD (SUNB)

The GPS station is on a two-storey building about 60 m south-east of Fordbridge Road.

The area covered by the GPS and the PS points to the south-east of Fordbridge Road is entirely underlain by the London Clay Formation and alluvium. River terrace gravels probably occur beneath the alluvium. Local borehole records suggest that bedrock lies more than 5 m deep. It is here presumed to lie permanently below the water table and so not to be liable to seasonal shrink-swell. Alluvium is the only formation present which is likely to be significantly compressible. The thickness of the alluvium is likely to be less than about 4 m, decreasing to less than 1 m at the road.

No artificial ground has been mapped in this vicinity by BGS, although some is likely to be present above the alluvium.

Some of these PS points may be on structures built on piles, or on thin alluvium, and so would be founded in gravel or London Clay rather than on alluvium, but there seems to be no easy way of distinguishing such points.

PS points along Fordbridge Road and to the north-west lie on terrace gravels directly overlying bedrock. No significant thickness of alluvium or of artificial ground is thought be present. These PS points are therefore significantly less susceptible to subsidence than the GPS station, and the PS points south-east of Fordbridge Road.

2.5 BUSH HILL PARK (BPGC)

The GPS station is in open ground about 150 m south-east of the clubhouse at Bush Hill Park Golf Club. It is based on a Berntsen Survey Marker (BSM), installed to a depth of about 3.8 m, probably in terrace gravel. All the selected PS points, except two, appear to be on or near the clubhouse. There are no PS points within 100 m of the GPS station.

The area covered by the GPS and all the PS points is entirely underlain by the London Clay Formation with overlying terrace gravels. These formations are not expected to be significantly compressible.

The terrace gravels appear to be at least 5 m in thickness, so the points are probably not liable to seasonal shrink-swell of the London Clay.

Two PS points (BPGC1 and 2), about 275 m north-west of the GPS station, are apparently related to structures sited within an area of a past gravel pit. This pit is shown on maps dated 1920 but had apparently been infilled and built over by 1938. Depending on the nature and thickness of the fill, these two points would be expected to be more susceptible to subsidence than the other PS points.

Otherwise, no differential movements between the GPS and the PS points, due to local geological conditions, would be expected.

2.6 ERITH (ERIT)

The GPS station is close to the tide gauge on a pier close to low water mark on the south side of the River Thames, about 500 m east-north-east of Erith Town Hall.

The GPS station is underlain by the Chalk Group, here presumed to lie permanently below sea level, and alluvium (including tidal river deposits). River terrace gravels probably occur beneath the alluvium. Local borehole records suggest that bedrock lies about 10 m below Ordnance Datum. Alluvium is the only formation present which is likely to be significantly compressible.

It is likely that the pier is founded in the terrace gravels, if not in the Chalk bedrock, and so should not be susceptible to compression of the alluvium.

There are no PS points within 100 m of the GPS site. The closest PS point appears to be about 268 m south-south-west of the GPS station. It lies within an area of made ground, overlying terrace gravels, overlying Chalk bedrock. This site should not be susceptible to local ground movement. Although the surface formations differ from those at the GPS station, no differential movements between the GPS and the PS points, due to local geological conditions, would be expected.

2.7 GRAVESEND GRAMMAR SCHOOL (GGSC)

The GPS station is in open ground about 50 m east-south-east of the main school buildings. It is based on a Berntsen Survey Marker (BSM), installed to a depth of about 5 m and so very probably in the Chalk bedrock.

The PS points associated with the southern end of the School buildings (GGSC9, 10, 13, 14) and also to the north-east of the GSP station (GGSC1) all coincide with a thin layer (probably between 1 m and 3 m thick) of the Thanet Sand Formation, overlying the Chalk Group. The northern end of the School buildings (associated with PS points GGSC 5, 6, 7, 8) is founded directly on the Chalk. There is a less than 50% chance that GGSC 7 and 8 are instead founded on the Thanet Sand, but if so, then it would be in a position where the Thanet Sand is only a few metres thick, at most. It therefore seems unlikely that there would be significant differential movement between PS points GGSC 5, 6, 7, 8, due to local geology.

PS points east of the GPS station (GGSC11, 12, 15, 16, 17, 18, 20) are founded on the Chalk. PS points in the area of housing south-south-west of the GPS station (GGSC 19, 21, 22, 23, 24) are founded on the Thanet Sand Formation, where it is about 5 to 10 m thick.

No superficial deposits and no artificial deposits have been recorded east of Church Walk. Near surface, the bedrock is probably permanently above the water table. No differential movement between the GPS points east of Church Walk or south of the school would be expected, due to local geological conditions.

The PS points west of Church Walk all occur in an area where the Chalk is overlain by head deposits. These are likely to be composed of gravelly, sandy, silty clay or clayey, gravelly sand or silt, and are probably between 1 and 3 m in thickness.

Differential subsidence between the larger buildings east of Church Walk and the smaller buildings west of Church Walk is a possibility.

The Chalk at this site is prone to dissolution, especially where it is overlain by the Thanet Sand Formation. This could give rise to differential settlement between the GPS station and any of the PS points, although where settlement is associated with dissolution it tends to be large, obvious and localised.

2.8 GRAIN (GRAI)

The GPS station is adjacent to Harvest Cottages, about 1 km south-west of Grain village. There are no PS points within 100 m of the GPS station.

The GPS station lies on river terrace gravels, probably up to about 5 m thick, overlying the London Clay Formation, so the GPS station is probably not liable to seasonal shrink-swell of the London Clay.

There is a gravel working within about 300 m north-east of the GPS station. Otherwise, no artificial ground has been recorded in this vicinity.

2.9 GREENWICH PARK (GRPK)

The GPS station is in open ground about 500 m south-south-east of the Royal Observatory. It is based on a Berntsen Survey Marker (BSM), installed to a depth of about 2.0 m in the Harwich Formation.

The GPS station and the PS points are all founded on the Harwich Formation, here probably composed mainly of sands and gravels and about 5 m thick.

No superficial deposits have been recorded in this vicinity. None of the PS points appears to be underlain by artificial ground.

Underground working of the Chalk is known to have occurred in the Blackheath Park area, and this has given rise to subsidence in places. However, as with dissolution, settlement associated with underground working tends to be large, obvious and localised.

Otherwise, no differential movements between the GPS and the PS points, due to local geological conditions, would be expected.

2.10 MILL PLAIN (MIPL)

The GPS station is near the south end of Oak Hill Gardens, in the east of Walthamstow Forest. It is based on a Berntsen Survey Marker (BSM), installed to a depth of about 4.1 m, probably in London Clay but possibly in terrace gravels.

All the nearby PS points lie on river terrace gravels, probably about 3-4 m thick, overlying the London Clay Formation. As the river terrace gravels are not at least 5 m thick, the site is possibly affected by shrink-swell behaviour of the London Clay.

No artificial deposits have been recorded in this vicinity.

No differential movements between the GPS and the PS points, due to local geological conditions, would be expected.

2.11 RICHMOND TIDE GAUGE (RICH)

The GPS station is at the north end of Richmond Lock adjacent to the tide gauge, on the north side of Richmond Footbridge, which crosses the River Thames.

The area covered by the GPS and the PS points on or close to the footbridge is entirely underlain by the London Clay Formation, covered by river terrace gravels and alluvium. Local borehole records suggest that bedrock lies more than 5 m deep. It is here presumed to lie permanently below the water table and so not to be liable to seasonal shrink-swell. No artificial ground has been mapped in this vicinity by BGS, although some is likely to be present above the alluvium.

Alluvium is the only formation present which is likely to be significantly compressible. However, Richmond Lock and the Footbridge are assumed to be founded in river terrace gravel, if not in the bedrock. Only one PS point, south of the south end of the Footbridge (RICH8), appears to be associated with a structure that might be founded on alluvium, and so which might be liable to subsidence due to compression of the alluvium.

The thickness of the alluvium is likely to be less than about 4 m, decreasing to less than 1 m near the bend in Ranelagh Road, about 100 m west of the footbridge, and at St Peters Road, about 100 m south-west of the footbridge. PS points further to the west and south-west lie on terrace gravels directly overlying London Clay bedrock. No significant thickness of alluvium or of artificial ground is thought be present. These PS points are therefore significantly less susceptible to subsidence than the PS point south of the Footbridge.

2.12 RIDDLESDOWN ROAD (RIDD)

The GPS station is in open ground about 100 m east of Keepers Cottage, on Riddlesdown.

The GPS station and PS points are all founded on the Chalk Group. Near surface, the bedrock is probably permanently above the water table. The area north-eastwards from Riddlesdown Road is underlain by clay-with-flints, that overlies the Chalk. The nominal positions of two of the selected PS points (RIDD3, 4) lie within the clay-with-flints, very close the edge of the mapped outcrop, but the corresponding structures are almost certainly founded in Chalk, like the other survey points.

PS points to the north and west of Keepers Cottage (RIDD 18-23) possibly lie in an area mapped as Made Ground, but it is likely that this refers to an archaeological embankment, and the corresponding structures are probably not liable to subsidence.

No differential movements between the GPS and the PS points, due to local geological conditions, would be expected.

2.13 SILVERTOWN (THAMES BARRIER) (SILV)

The GPS station is at the north end of the Thames Barrier and is founded on the structure that forms the start of the barrier and the sea wall, which is in all probability founded in bedrock, possibly in the Chalk.

PS points to the north-east of the GPS station appear to be associated with single storey or two-storey industrial buildings. In general, the area to the north and north-east of the Thames barrier is ground underlain by Artificial Ground laid over alluvium (including tidal river deposits). The alluvium in turn overlies river terrace gravels resting on Thanet Sand Formation or Lambeth Group. Alluvium is the only formation present which is likely to be significantly compressible. Differential subsidence between these PS points and the GPS stations is therefore likely.

PS points to the south of the GPS stations all appear to be on the Thames Barrier. This is founded in Chalk bedrock. Two of the piers have no associated PS points; the rest have between 4 and 9 PS points, for which the AG/GPS-aligned ground velocity values are averaged as follows. Pier 1 (at the northern end of the Barrier): -1.0; Pier 4: -0.6; Pier 5: -1.0; Pier 6: -1.4; Pier 7: - 1.6; Pier 8 (at the southern end of the Barrier): -1.7 mm/year.

It is thus arguable that the southern portion of the Barrier is subsiding by 0.25 to 0.5 mm/year faster than the northern part, although this amount is close to the limits of resolution of this data. The Thames Barrier lies on the northern limb of the Greenwich Anticline. It is directly along strike from the NE-SW trending Greenwich Fault. Although current BGS maps show no faults at the Thames Barrier, Fookes (2006) records small-scale faulting in the underlying Chalk, found during site investigation. He postulates that the Greenwich Fault continues under the Thames Barrier, out into Essex. So, it is possible that neotectonic fault displacement could occur between Silvertown and Charlton (on the south bank of the Thames).

However, differential subsidence between the PS points associated with the more northerly piers of the Thames Barrier and the GPS stations is not likely.

2.14 SOUTHEND PIER (SOPR)

The GPS station is adjacent to the tide gauge on the Pier, near its southern end. There are no PS points within 400 m of the GPS site.

The Pier is sited on tidal flat deposits, probably overlying river terrace gravels, overlying London Clay Formation. The Pier is assumed to be founded in the London Clay, which is here permanently below sea level and so not liable to seasonal shrink-swell.

2.15 THURNHAM (THUR)

The GPS station is in open ground on the North Downs, approximately 850 m north of Thurnham Church.

The GPS station is sited on the Chalk Group. No superficial deposits and no artificial deposits have been recorded at this site.

A PS point about 169 m north of the GPS station (THUR1) is likely to relate to a structure founded in clay-with-flints. The other three selected PS points very probably relate to a structure founded in the Chalk.

Differential movement due to local geological conditions is likely between THUR1 and the other survey markers.

2.16 TILBURY (TILB)

The GPS station is adjacent to the tide gauge, on the north bank of the River Thames at the western side of Tilbury Docks, about 400 m south-south-west of Northfleet Hope House.

The site is on ground underlain by Artificial Ground laid over alluvium (including tidal river deposits). The alluvium in turn overlies river terrace gravels resting on the Chalk Group. Alluvium is the only formation present which is likely to be significantly compressible.

PS points north of the GPS station (TILB1-3) appear to be in the same geological situation as the GPS station. Those PS points south of the GPS station (TILB4-6) may be in the same situation but they relate to structures that have different foundations that have presumably been piled into terrace gravels or the bedrock. Differential movement due to local geological conditions between these PS points and the other survey points is therefore possible.

2.17 TOWER PIER (TOPR)

The GPS station (destroyed during a rebuild of Tower Pier) was founded on the sea wall on the north bank of the River Thames, adjacent to Tower Pier, immediately south-west of the Tower of London.

The site is underlain by Artificial Ground laid over alluvium (including tidal river deposits). The alluvium in turn overlies river terrace gravels resting on London Clay Formation. Alluvium is the only formation present which is likely to be significantly compressible. The London Clay is here permanently below sea level and so not liable to seasonal shrink-swell.

The tide gauge is on a structure that is probably piled into the terrace gravels or London Clay. Differential movement between the tide gauge and the GPS site is therefore possible.

PS points identified to the west and north of the GPS station appear to be associated with one of several high-rise buildings: Three Quays, Tower Place and All Hallows Church. Those to the east of the GPS appear to be associated with various elements of the Tower of London.

The Three Quays site has similar geology to the GPS site, but the building is presumably founded below the alluvium. Tower Place is a modern building, constructed during the period of this project, founded in London Clay. All Hallows Church is sited on river terrace gravels overlying London Clay. The Tower of London is founded essentially on London Clay.

Some differential movement between the GPS station and most of the PS points (excepting those immediately to the east of the GPS station, which could be in a similar situation) could occur.

3 Procedure for geological interpretation of the PSI data

The following account concerns the geological interpretation of Version 2 of the PSI dataset, as supplied by NPA in May 2006. Compared with Version 1, this dataset includes the application of a shift of -0.66 mm/year to displacement values and velocities, so aligning the average velocity for each PS point with the GPS and AG measurements, such that the PSI data represent absolute ground motion.

Version 2 of the PSI dataset had also been re-projected to British National Grid (OSGB'36) coordinates, and also re-projected to the vertical. This allowed it to be directly compared with a range of geological and hydrogeological datasets held by BGS, within a geographic information system (GIS) employing the ESRI software system ArcMap 9.1.

Prior to the comparison, the average annual ground velocity values (mm/year) for all the PS points (950 381 values) were plotted in several ways within the GIS:

- As various scatter plots, with values grouped into different classes (some with a selected range of data, e.g. all values between +1 and –1 mm/year, hidden); and coloured in different ways (Figure 1A, 1B, 1C).

- As various smoothed grids (Figure 1D); some with a selected range of data hidden. The grids used were based on average values within an array of 50 m cells, using IDW (Inverse Distance Weighting) criteria over a radius of 250 m, or 'nearest neighbour' criteria.

These plots showed that the average ground velocity values are far from being evenly distributed (Figure 1). Some areas are dominated by positive average velocity values (shown in blue) and some by negative average velocity values (shown in yellow, orange and red). That is, between 1997 and 2005, some areas have mainly undergone uplift (blues) and some have mainly undergone subsidence (reds). In some areas, the data plot creates a 'stippled' effect where PS points indicating uplift and subsidence are approximately balanced.

In order to simplify the process of interpretation and also to help ensure that the velocity data were interpreted in a reasonably consistent manner, a variety of these plots were inspected to identify 'domains' of approximately uniform average ground velocity characteristics, and to note lineaments within the data distribution. This is analogous to processes employed in the geological interpretation of satellite images.

Although different plots tended to enhance different aspects of the data distribution, a reasonably consistent pattern emerged (Figure 2). (It should be noted that the colour scale used to classify average velocity in Figure 2 uses intervals of 0.5 mm/year between +2 and –2 mm/year, and larger intervals at more extreme values.) This map of the 'average ground velocity domains' is intended to be viewed at relatively small scales: in many places the domain boundaries can be placed only approximately. Also, the overall high density of data points means that in scatter plots the perception of domain boundaries can differ at different scales. However, it should be emphasized that the delineation of domains and lineaments was, except very locally, undertaken without reference to the geoscience datasets. In a few places, the domain boundaries were subsequently modified at larger scales (about 1: 50 000) (e.g. Figures 10 and 19), but this was not done systematically.

This interpretation of domains is thus based on a qualitative, visual inspection of graphic data plots. It is, however, substantiated by calculated averages of ground velocity for the PS points within each domain (Table 1). Other types of quantitative analysis would possibly reveal additional systematic heterogeneities in the distribution of average ground velocity.

As shown in Table 1, the average ground velocity domains have been ranked from 1 to 6, with individual domains of each rank given suffix letters to assist reference (Figure 3). Domain 1 has mainly positive average ground velocities (it has probably experienced uplift, in general) and Domains 4, 5 and 6 have mainly negative ground velocities (they have experienced subsidence, in general). The average of all the ground velocity determinations within Domains 2 and 3 are negative, indicating that on the whole these domains have also undergone subsidence. However, considering the errors in the CGPS, EGPS and PSI it is not possible to make any conclusions regarding velocities of less than about 0.5 mm/yr. With this in mind, it is therefore possible that Domain 1 could be uplifting more rapidly, while Domain 2 is slightly uplifting and Domain 3 is stable, or that Domain 1 could be stable or slightly subsiding while Domains 2 and 3 are definitely subsiding. Nevertheless, the occurrence of net uplift in Domain 1 is supported by some aspects of the local Quaternary geology, as noted below.

Although the significance of the 'stippled' value distribution in Domains 2, 3 and 4 is unclear, and would merit closer investigation, it seems likely that these domains are of intermediate and mixed character, with some parts having undergone subsidence and some uplift.

As analysis proceeded, it became apparent that some of the smaller domains are probably controlled by processes acting locally at relatively shallow levels (within 100 m of the surface). If these domains are disregarded, then a generalised pattern of average velocity can be discerned, which is presumed to approximate to the 'regional pattern' of average ground velocity (Figure 4). Domain Gi appears to be undergoing uplift, on the whole, whereas Domains Giv and Gv appear to be subsiding. Ignoring local perturbations caused by near-surface processes, Domains Gii and Giii could be experiencing slight subsidence, or neither subsidence nor uplift. This generalised pattern bears little apparent relation to 'near-surface' geology but, as discussed below, can be correlated with elements of the deeper geological structure.

Scatter plots of the average ground velocity and the interpreted domain maps were systematically compared with a variety of geological and hydrogeological datasets. Comparison was undertaken visually on a 19" VDU, using the GIS to display selected datasets at various scales (between about 1:420 000 and 1:20 000), as appropriate. It was found that some of the gridded representations of the data tended to enhance extreme values where these occur adjacent to data lacunae, and that in general they were less amenable to interpretation at the larger scales used.

3.1 GEOSCIENCE DATASETS

3.1.1 DiGMapGB50

This digital geological map is based on the published BGS 1:50 000 scale geological map sheets. The geological information shown on the paper maps has been digitised under five themes, each of which can be displayed individually or in combination with other themes. These are:

1. Bedrock formations (pre-Quaternary deposits) (Figure 5)
2. Superficial deposits (Quaternary-aged deposits) (Figure 6)
3. Artificially modified ground (mainly worked ground, made ground or infilled ground)
4. Mass movement deposits (landslide deposits)
5. Geological lines (mainly faults) (Figure 13).

3.1.2 Geohazard data from GeoSure

These derived geological datasets, prepared by BGS, are based largely on GIS analysis of DiGMapGB50, in combination with other datasets such as a high-precision DTM and known physical properties of individual formations or deposits. They help predict local susceptibility to ground movement as a consequence of six major natural geological hazards:

- *Shrink-swell clays*: the propensity of clay-rich subsoils to change volume with changes in moisture content
- *Compressible ground*: the propensity of the ground to undergo a volume reduction under load (Figure 8)
- *Collapsible ground*: the possible presence of metastable soil structures associated with 'brickearth' deposits, liable to abrupt collapse under load when water-saturated
- *Dissolution*: the propensity for subsidence associated with water-soluble rocks (limestones, gypsum, halite). In this region, the hazard is associated only with the Chalk.
- *Running sand*: the propensity for water-saturated sand to flow into boreholes or excavations
- *Slope stability*: the propensity for landslip formation

3.1.3 Holocene thickness – 1997

This map (Figure 7A) of the thickness of Holocene (late Quaternary) deposits (comprising alluvium, peat, tidal flat deposits, etc.) in parts of London and the Thames estuary is derived from part of the 'geological database', created by BGS as part of the EA/NERC CONNECT B project (Bingley et. al. 1999). It comprises part of the 'geological database' mentioned in Objective 08. (The Holocene is the period of time since the last glaciation; from 11 500 years ago to the present day). The map represents the difference in height between the base of the Holocene (as modelled in three dimensions using borehole records) and the land surface, or sea level.

3.1.4 Holocene thickness – 2006

This map (Figure 7B) of the thickness of Holocene deposits in London and the Thames estuary is derived from a 3D model created for a project within the current BGS strategic programme. In contrast to the 1997 model, it represents the difference in height between the base of the Holocene as modelled in three dimensions using borehole records (a different set to that used previously) and either the land surface or the river bed.

3.1.5 Peat thickness

Holocene deposits tend to compress, either under their own weight (natural consolidation) or under a superimposed load (typically either made ground, built structures, or flood water).

Peat is by far the most compressible material found in Holocene deposits. Data for the thickness of peat present in the Thames alluvium were extracted from borehole records. Two sets of records were used: those encoded as part of the EA/NERC CONNECT B project (which form another part of the geological database mentioned in Objective 08), and those held within the BGS corporate database 'Borehole Geology' up to 15 August 2006. Some of the data appears in both datasets, so they were combined.

A scatter plot of the variation in total peat thickness (Figure 9A) shows some non-random variation. Areas in which peat thickness generally exceeds 2 m boundaries are also shown in Figure 9. These were identified by visual inspection and drawn by hand. They indicate that thicknesses in excess of 2 m mostly occur in a restricted area, downstream of the Thames-Lea confluence, with peat thickness generally decreasing both upstream and downstream of this area.

It has been suggested that the greatest peat thickness occurs where the Chalk Group or Thanet Sand Formation (which together comprise the major aquifer in the London area) directly underlie the Quaternary, so allowing groundwater to discharge into the alluvium and enhancing non-saline environments in which peat-forming vegetation would thrive (Bingley et al., 1999). The presently available data for peat thickness support this hypothesis only in the most general way: exact correlation between the subcrop of the major aquifer and areas of thickest peat could not be demonstrated.

The distribution of the thickest peat deposits is likely also be a function of the width of the Thames floodplain, which is possibly controlled by neo-tectonic motion on the Wimbledon-Greenwich fault zone (see below). Downstream, peat development becomes less with increasing salinity.

3.1.6 Regional groundwater level data

When water is extracted from the ground (for public water supply, for example), the ground surface tends to subside as the water table falls. If the water table recovers, then some uplift of the ground surface can be expected, but only by up to about 10 per cent of the subsidence (Freeze and Cherry, 1979).

Since 1991, the Environment Agency has published an annual report on changing groundwater levels in the Chalk-Thanet Sand aquifer in the central London basin. Each report includes a contour map showing groundwater levels for January of the year of the report, derived from observations in water boreholes, together with a short discussion of the observed changes (Figure 11).

For this project, the EA maps for Jan 2006 and Jan 1997 were each obtained as a digital grid, and the older data was subtracted from the younger. The resultant grid thus represents the overall change in groundwater level during a period approximately corresponding to the period of acquisition of PSI data used for this project. Positive values represent areas where groundwater has risen during that period, on average, and negative values show where it has fallen (Figures 12 and 13).

Note that this data does not take account of minor aquifers in the superficial deposits. It is felt that the variations of groundwater level within these minor aquifers are likely to show little, if any, net change over the period of the project.

3.1.7 Geophysical Data

Data from regional aeromagnetic surveys and regional gravity surveys were processed in a variety of standard ways to investigate possible relationships between changes in land level and deep-seated geological structures. Variations in these two geophysical datasets in the London area relate to geological formations occurring beneath the Chalk Group, mostly of Palaeozoic or Proterozoic age.

The gravity and magnetic anomaly maps of the London area show small departures from the expected value of the Earth’s gravity and magnetic field (anomalies) caused by variations in the density and magnetisation of rocks within the crust. They can be used in conjunction with borehole and seismic information to determine the concealed geological structure beneath London. Most of the gravity and magnetic material provided for this study is derived from Busby et al. (2006).

Gravity data

The gravity data are displayed as Bouguer gravity anomaly maps which incorporate a ‘Bouguer’ correction that allows for the gravitational attraction of the rocks between the observation point at the surface, and sea-level. The Bouguer correction removes the gravitational effect due to topography in areas of high relief and leaves the gravity anomaly due to geological structure (Figure 14).

3D gravity modelling has been carried out on a broad regional scale to reveal structures associated with Palaeozoic ‘basement’ rocks that are masked by the gravity expression of the overlying Mesozoic and Cainozoic formations. The modelling technique known as ‘gravity stripping’ calculates and removes the gravitational effect of individual rock layers where the depth to the base, the thickness and the mean density of each layer have been inferred from interpretation of deep boreholes and seismic surveys.

Magnetic data

An aeromagnetic survey of London and the south-east of England was carried out between 1955 and 1957. The area covered by central London was not flown due to the overwhelming electrical interference from the electric railways and other anthropogenic sources.

Magnetic maps are typically shown as Total Field magnetic anomaly and Reduced to Pole anomaly. The latter is the Total Field anomaly converted to the field that would be observed at the magnetic pole (vertical field) (Figure 17). This has the advantage of simplifying the anomaly pattern and adjusting the location of the peak anomaly to lie immediately over the source. However, if remanent magnetisation is present some distortion will occur.

Several standard techniques are used to enhance regional geophysical data. The enhanced gravity and magnetic images are shown as colour-shaded relief images that show anomaly amplitudes as colour and anomaly gradients as relief. Linear or arcuate features are attributed to faulting or fold structures whilst circular anomalies are generally associated with igneous intrusions or small local sedimentary basins.

Upward continuation: The primary gravity and magnetic gridded data have been further processed to enhance geophysical anomalies associated with near surface rocks and separate these from those associated with deeper sources. This process can be achieved by the method of upward-continuation. This process transforms the observed field to the field that would appear at some greater height. As the height increases so the response from narrow and shallow bodies diminishes, thus clarifying the response from deeper bodies and structure.

Residual anomaly: By subtracting the upward continued field from the observed field a series of residual anomaly maps can be produced. These can be considered as depth slices, and reflect the presence of bodies and structures, progressively deeper into the ground (Figure 14).

Vertical derivatives: The vertical gradient enhances the high frequencies at the expense of the low ones. This improves the resolution of near surface features, particularly where anomalies from adjacent bodies or bodies at different depths are overlapping.

Horizontal gradient: This enhances the response from near surface features and produces anomaly peaks along the edges of wide bodies (Figure 16).

3.1.8 Published interpretations of 'deep geology'

Existing interpretations of near-surface and buried geological structures, published in the London Memoir (Ellison et al., 2004) or the London and Thames Valley Regional Guide (Sumbler, 1996), were scanned and geo-registered so that they, too, could be directly compared with the other datasets within the GIS.

3.1.9 Topographical maps

In addition to the geoscience datasets, the following datasets were available for reference and location purposes:

- Ordnance Survey topographical maps at 1: 250 000; 1: 50 000 and 1:10 000
- 'Historical' 1:10 560 scale Ordnance Survey topographic maps, of various dates between about 1870 and 1950

4 Results of comparison with geological datasets

Although each of the datasets described above was systematically compared with the average ground velocity data, and with its 'domains' of variation, not all the geological datasets showed any correlation with average ground velocity, and some apparent variations in ground velocity could not be attributed to known geological variation.

Indeed, in some cases, no correlation was to be expected. For example, although running sand, dissolution, collapsible deposits and slope stability (natural geohazards assessed by the GeoSure themes) can cause significant subsidence, the ground movements tend to be very localised. The shrink-swell behaviour of clays can give rise to significant vertical ground movements (up to about 50 mm would be usual) over quite wide areas, but the movement is reversible and can be observed to follow seasonal variation in precipitation (Bingley et al., 1999). No systematic increase or decrease due to this phenomenon would be expected if observation occurs over complete seasonal cycles. (It might be, however, that some of the local heterogeneity in the PSI estimates of vertical velocity for individual PS points reflects local variation in ground movement due to shrink-swell).

Some of the datasets could not be fully evaluated because there are too few relevant PS points. For example, landslide deposits tend not to be built on. Thus very few PS points coincide with mapped landslides.

The remainder of this discussion deals only with positive correlations between the geological datasets and average ground velocity indicated by the PSI data.

Some degree of correlation was found between average ground velocity and the following phenomena:

1. Distribution of compressible ground
2. Fall in groundwater level in the Chalk-Thanet Sand aquifer
3. Faulting within the Wimbledon to Greenwich tectonic zone
4. ‘Geological basement structures’
5. Artificially modified ground

4.1 DISTRIBUTION OF COMPRESSIBLE GROUND

Compressible deposits are susceptible to either local or regional subsidence, due either to self-loading or imposed loading. Two types of compressible deposits are recognised in the London area: Holocene deposits (see above), which occur alongside rivers and estuaries, and ‘made ground’, which can include poorly consolidated landfill, for example. Holocene deposits can also undergo significant shrinkage through desiccation of the topmost few metres of sediment. This tends to occur in areas where Holocene deposits have been protected from flood. It is not significantly reversible.

Where Holocene deposits are most extensive and generally thick, there is a clear correlation between areas prone to subsidence and compressible ground. Domains 5F, 6D, 5C and 6E coincide with extensive areas of Holocene deposits in the valleys of the Lea, Thames and Medway (Figure 6). Other extensive areas of Holocene deposits have coincident few PS points. Note that Domains 6A to 6C and 5A and 5B do not coincide with occurrences of Holocene deposits –see discussion of groundwater levels and artificially modified ground, below.

4.1.1 Holocene thickness

The distribution of PS points within the area of the two Holocene thickness models is very uneven, with their density tending to be least where the Holocene sequence is thickest (Figure 7). However, where the Holocene is in the range up to 20 metres thick, there seems to be no correlation between sediment thickness and amount of subsidence.

Conversely, in the upper parts of river catchments, including the River Thames upstream of Tower Bridge, where alluvium can be expected to be less than 5 m thick, in general, areas of Holocene deposits show essentially the same range and distribution of average velocity values as in surrounding areas (Figure 8).

4.1.2 Peat thickness

Most of the data points for peat thickness lie in areas where PS points are relatively sparse. Where concentrations of the two datasets coincide, then no clear correlation between peat thickness and average ground velocity can be seen (Figure 9). For example, the general rate of subsidence is less in the Erith Marshes than in the West Thurrock Marshes, and around Tilbury, although the range of thickness of peat is similar in each area. Conversely, in the Thames Haven area, just west of Canvey Island, the rate of subsidence appears similar to that of West Thurrock, but the peat is generally thinner.

More detailed 3D models of the Thames Holocene deposits should allow a more detailed analysis of the PSI data in relation to lateral variation in the Holocene deposits.

4.1.3 Made ground

In many parts of the area, areas of compressible ground carry few PS points, so that possible correlation between compressible ground and average ground velocity cannot be fully assessed. However, where PS points coincide with potentially compressible made ground or infilled ground, no consistent contrast in average ground velocity can be seen, compared with adjacent areas (Figure 8).

There are some areas of apparent average uplift (up to about 1 mm/year) or relatively slight subsidence within the Thames Holocene deposits. These anomalous areas occur where there is extensive building on areas of made ground. The most notable coincide with the Dagenham motor works [549540 182135], mill buildings at Purfleet [555820 177900], and the Canning Town and Stratford areas near the mouth of the Lea Valley [539125 182450]. At Dagenham (Figure 10), the eastern edge of the anomaly is particularly clearly marked and coincides with a drainage channel.

The reasons for anomalous ground movement in these sites is not immediately obvious. However, these areas have apparently been built on for relatively long periods. For example, at Dagenham the ground west of the drainage channel (with the main motor works) was developed prior to 1938, whereas the ground east of this channel (used mainly for hard standing areas) was developed later than 1951.

The most likely explanation seems to be that in these anomalous areas the alluvium (and overlying made ground) has reached its effective limit of compression, and so the anomalous areas are instead experiencing the same rate of ground movement as found in adjacent areas, beyond the extent of the alluvium. Alternatively, it might be that the Dagenham motor works is founded on deep piles, and so would not be susceptible to compression of the alluvium. Although this explanation probably applies to jetties at the riverside, for example, it seems unlikely that it could apply to all the built structures within these areas of anomalous ground velocity. Note that if the load is increased, then further subsidence might take place, particularly where peat is present.

In other developed areas on alluvium, such as the east side of the Isle of Dogs [538400 180040] and ground between Bermondsey and Deptford [536215 178267], there is no reason to suspect any local contrasts in the maturity of the made ground. Areas of slight uplift within the alluvium at these places might mark local areas where the sequence is thin or where there are local variations in composition. Alternatively, PS points indicating positive average ground velocity might relate to deeply founded buildings.

4.2 FALL IN GROUNDWATER LEVEL IN THE CHALK-THANET SAND AQUIFER

A grid representing the change in groundwater level in the main Chalk-Thanet Sand aquifer between January 1997 (Figure 11) and January 2006 was compared with the average ground velocity domains (Figure 12).

The most striking correlation occurs in the Merton area of south-east London, where groundwater levels have been lowered by at least 30 m since 1995 as a consequence of abstraction at public water supply boreholes. The largest negative anomaly is centred close to the Merton Abbey public water supply well [526850 170010] (BGS Index No: TQ27SE 748), one of a number of sites in this part of the London area where water is abstracted from the Chalk at depths in excess of 70 m. (Note, however, that the water table remains at a level within the

London Clay). The Merton Abbey well was not used between 1987 and 1995, when test pumping resumed.

Depression of the water table in this area can seen in the record of an observation borehole at Springfield Hospital, about 2.3 km north of Merton Abbey well, [527160 172540] (BGS Index No: TQ27SE 45) (Environment Agency, 2005).

The area of depressed groundwater level around Merton coincides with the area of subsidence identified here as Domain 5A (Figures 12, 13). No other explanation for the existence of this domain has been identified. The north-west edge of Domain 5A is coincident with the Wimbledon Fault (see below). The north-west edge of the area of lowered groundwater is aligned with the same structure, and with the lineaments in the ground velocity data, although the low resolution of the groundwater level data does not necessarily reveal the true extent of the cone of depression around this pumping station. Nevertheless, it appears that fractures parallel to the Wimbledon Fault are exerting some control on groundwater movement.

A smaller anomaly, to the north-east of Merton, coincides with the Honor Oak pumping station, Camberwell (BGS Index No: TQ37SE 144; [535300 174850] (Figure 12). This also extracts water from the Chalk aquifer at a depth of about 70 m. No subsidence closely associated with Honor Oak can be discerned in the PSI data. However, some ill-defined areas of subsidence in Domain 4C might be related to groundwater abstraction, particularly where the aquifer is deeply covered by younger deposits.

Large-scale dewatering of the Thanet Sand Formation associated with the construction of the Channel Tunnel Rail Link (CTRL) took place between Stratford and East Ham during 2001-2004. The net groundwater lowering of between –5 and –10 m in this area is partly associated with this operation and partly with groundwater abstraction for public water supply.

Domain 5B, in which negative ground velocity is somewhat greater than in adjacent parts of Domain 4F (which has a similar geology) appears to coincide with part of this zone of groundwater depression. The north-westerly extent of Domain 5B is close to the major lineament in average ground velocity distribution, and so is likely to have been controlled by faults, in an analogous manner to that found in Domain 5A. No faults have been mapped at surface in this position but faulting in the London Clay under London is known to be significantly more extensive than mapped, and the coincidence of the portion of the velocity data lineament in Domain 5B with an abrupt lateral change in the gravity field (Figure 16) indicates the probable presence of major faults at depth.

There is another, weaker, correlation between groundwater change and the average ground velocity domains north of London, where the eastern portion of Domain 4A (east of Borehamwood) extending east of the Lea Valley into the northern part of Domain 4F, corresponds to a zone in which groundwater level has dropped, relative to the levels within the adjacent domains 3C and 3E. Note that the western portion of Domain 4A, in which groundwater levels have risen, corresponds to a region where the Chalk aquifer is unconfined (i.e. it is not covered by Palaeogene deposits) allowing more direct aquifer recharge (Figure 5). The groundwater levels in the unconfined Chalk declined significantly during dry weather in 1995 and 1996 but have since recovered.

It may be significant that the Mill Plain EGPS station (in the centre of Domain 3D), which recorded a significantly higher rate of ground subsidence (-2.39 mm/year) than the surrounding stations Silvertown (-1.80 mm/year), Barking Barrier (-1.88 mm/year) and Bush Hill Park (-0.27 mm/year), lies within an area in which groundwater levels have fallen by up to 5 m during the course of the project.

Small areas of greatest net groundwater recovery (more than 15 m rise), especially those in the south-west of the area, tend to coincide with areas with few PS points. This is possibly a consequence of enhanced recharge in less built-up areas, which have a smaller proportion of surface sealing. The other areas all occur at the edge of the data grid, and could reflect poor data coverage. Overall, little evidence for uplift associated with groundwater recovery can be seen.

There is no other clear correlation between the change in groundwater level between Jan 1997 and Jan 2006, and average ground velocity. However, the groundwater level data has a relatively coarse resolution and more detailed data might reveal some further correlation.

4.3 FAULTING WITHIN THE WIMBLEDON TO GREENWICH TECTONIC ZONE

Linear discontinuities, trending north-east to south-west, are apparent in the distribution of average ground velocity values (Figures 2 and 4). The relative abruptness of the change in average ground velocity apparent at these lineaments suggests that they are controlled by faults at a relatively shallow level, probably at rockhead. If a change were marking a structure at a deeper level, a more diffuse change would be expected. Indeed, this may be the case in the north of the area, where the major lineament becomes less well-defined.

These lineaments are sub-parallel to the nearby *en echelon* swarm of faults which has been mapped in south-west London: principally the Wimbledon, Streatham and Greenwich faults (Ellison et al., 2004) (Figure 13). The Wimbledon Fault is downthrown on its south-east side; the other two are down-thrown in the opposite sense.

Part of the more extensive lineament is coincident with part of the Wimbledon Fault, and the north-west margin of Domain 5A is partly bounded by the Wimbledon Fault (Figure 13). As noted above, the same fault zone also appears to control the north-western extent of Domain 5B. Note that fault movement caused by groundwater abstraction is likely to be restricted to those parts of the fault above the water table. It is also noteworthy that the width of the Thames floodplain increases markedly downstream of this major lineament, as shown by the outcrop of the Holocene deposits (Figure 6). This implies a sense of ‘down to the south-east’ neotectonic motion on faults parallel to the Wimbledon and Greenwich faults. (‘Neotectonic’ refers to earth movements on currently active faults and more generally to those post-dating the main Alpine period of mountain-building, in mid-Cainozoic times). If correct, this finding implies that additional sub-parallel faults, so far unmapped, lie north-west of the Greenwich Fault.

These correlations demonstrate local control of the patterns of average ground velocity by near-surface tectonic structures. They imply that some differential ground movement has been accommodated by neotectonic movement on the Wimbledon Fault, and probably also on sub-parallel, unmapped faults.

4.4 ‘GEOLOGICAL BASEMENT STRUCTURES’

Regional geophysical surveys, supported by information from seismic reflection profiles and boreholes, show that the project area is underlain by portions of three geological terranes within the pre-Mesozoic basement (Figure 14).

The north-western part of the area is underlain by the Midlands Microcraton, an area where Proterozoic rocks occur at relatively shallow depths, and which has been relatively tectonically stable during the Phanerozoic. Structural trends are complex. The north-eastern part of the area is underlain by a portion of a Caledonide fold belt, formed during mid-Palaeozoic times, in which the dominant structural trends are north-west to south-east. The southern part of the area includes the northern margin of a Variscan fold belt, formed in late Palaeozoic times. This terrane is represented by arcuate structural trends, oriented approximately east-west (Pharaoh et al., 1993).

The Variscan fold belt was the site of basin subsidence during the Mesozoic and basin inversion during the Cainozoic, whereas the Midlands Microcraton and the Caledonide foldbelt (together forming the London Platform) remained relatively stable during that time. Note that Figures 14 and 15 show the northern margin of the Variscan fold belt somewhat further north than do previous interpretations. For example, Ellison et al. (2004) ascribe the area of the large gravity ‘low’ in the south of the project area (Figure 15) to ‘a zone of transition between the London Platform and the Variscan fold belt’. This gravity low probably marks a very thick sequence of post-Caledonide strata (probably of Devonian age). A zone of north-east to south-west trending basin margin faults is thought to separate the area of the gravity low from the Midlands Microcraton, as indicated by linear features in the horizontal gradient of the gravity field (Figure 16). This basin margin fault zone is likely to be quite complex at depth, becoming simpler upwards. Faults and folds seen in the bedrock under south-west London (the Wimbledon to Greenwich tectonic zone) formed by later movement in this structural zone.

The generalised ground velocity domains Gi and Gii coincide with a gravity high within the Midlands Microcraton, in the west of the area (Figure 15). There is no correlation between these domains and any feature of near-surface bedrock geology. The south-east margin of Domains Gii and Giii lie parallel to the lineament in the average velocity data, to the Wimbledon Fault, and to the faulted south-east margin of the Midlands Microcraton (Figure 15). This correlation implies that in the London area, isostatic uplift is confined within the Midlands Microcraton, with the extent of differential movement between Gii, Giii and Giv being controlled by deep-seated tectonic structures.

The cause of the isostatic uplift in Domain 1/Gi (and perhaps in Gii) is not certain. The coincidence of Gi with the centre of the gravity high implies a causative relationship. The gravity high indicates the presence of relatively dense rocks, relatively close to the surface. These are likely to be of Early Palaeozoic or Proterozoic age, forming a ridge between Late Palaeozoic basins to the north-east and south-west (Figure 14). The presence of this ridge implies a zone of relative tectonic uplift, apparently enhanced at its south-eastern end by interaction with uplift at the faulted margin with the Devonian basin under south London. The presence of Domain Gi indicates that the tectonic structures that control the position of the ridge have in some way been reactivated at the present time.

The contrast in relative movement between Domains Gii and Giii (slight subsidence or possible slight uplift), compared with the somewhat greater rate of subsidence in Domains Giv and Gv, is possibly a consequence of net erosion during the Quaternary in the middle and upper Thames Basin (Bridgland, 2006) and further to the west (Watts et al., 2005). (Alternative hypotheses are noted in those papers.) In this connection, it may be noted that Domain 1/Gi has few superficial deposits (Figures 6 and 18). In this respect it is similar to portions of domains 2B, 3C and 4B, to the north, although not to domains 2A, 3A, and 3B to the south and east, which largely coincide with river valleys.

Indeed, it should be noted that although the River Thames flows generally eastwards across the Palaeogene outcrop in the London Basin, between Windsor and Chiswick its course traces a broad loop by about 10 km southwards (Figure 18). The area within this loop is underlain by unusually broad outcrops of the Taplow Gravel and the Kempton Park Gravel, which form two of the lowest river terrace deposits. This relationship suggests that uplift centred on Domain Gi has occurred during deposition of these river terraces, in the later part of the Quaternary, so diverting the River Thames southwards.

The course of the River Colne is also appears to be anomalous, in that it flows south-west and then south before joining the Thames (Figure 18). The south-westerly flowing portion follows a pre-glacial valley. However, it seems possible that the course of the southerly-flowing portion (which might be expected to flow south-eastwards, like the Colne’s north-western tributaries) is in part controlled by uplift of Domain Gi.

Several other correlations between ground velocity domain boundaries and basement structures suggest that some elements of the regional ground velocity are controlled in a general way by neotectonic movement on deep-seated structures.

The eastern edge of generalised domain Giv approximately follows the margin of the large gravity lows in the centre of the project area and the north-eastern portion of domain Giv follows the Caledonide structural trend (Figure 15). Some parts of the south-eastern margin of Domain 4E coincide with basement structures highlighted by the horizontal gradient analysis (as marked by red dashed lines in Figure 16), and the north-eastern margin of Domain 4H likewise follows structural elements within the Caledonide fold belt.

There is also an approximate correlation between the generalised domains and the regional aeromagnetic anomalies (Figure 17).

4.5 ARTIFICIALLY MODIFIED GROUND

A linear zone of subsidence (Domain 6C) between London Bridge station and Green Park, previously identified by NPA Group, has been associated with part of the route of the Jubilee Line Extension (http://www.npagroup.com/insar/apps/london_psi.htm) (Figure 19). NPA have found rates of as much as -7 mm/year within this zone of subsidence. The JLE was built between 1995 and 1999.

A similar zone of subsidence, some several hundred metres wide, occurs in Battersea between Nine Elms and Wandsworth (Domain 6A). This has been reported to be associated with construction of a utilities tunnel for London Electricity. No evidence for local variation in the superficial deposits, that could explain this anomaly, can be discerned in local borehole records.

A small domain of localised subsidence (Domain 6B), several hundred metres across, is centred on the Sloane Square London Underground station (District and Circle lines). However, no causative relationship has been demonstrated.

The possible effects on average ground velocity of some made ground overlying alluvium was discussed under compressible deposits.

5 Key conclusions

In the London region, PSI data show that:

1. Regional patterns of uplift and subsidence are controlled, to some extent, by deep-seated geological structures.
2. There is also some local control by neotectonic movement on near-surface structures, such as the Wimbledon Fault.
3. Parts of the project area, north-west of the Wimbledon Fault and its lateral extensions, are prone to uplift or relatively slight subsidence. Uplift is centred on a gravity ‘high’ within the Midlands Microcraton.
4. The remainder of the project area is prone to subsidence.
5. Where Holocene deposits are extensive and thicker than about 5 m, the ground is generally prone to a greater rate of subsidence than found regionally.
6. In some areas, however, where thick Holocene deposits are overlain by old made ground, subsidence due to compression currently appears to be negligible and may have ceased.
7. Further analysis of patterns of subsidence within areas underlain by Holocene deposits requires the construction of an attributed 3D model of the deposits.
8. The PSI data has served to demonstrate clearly a close relationship between subsidence following water abstraction, and lines of faulting.

9. Groundwater abstraction and tunnelling can cause subsidence at a similar rate to that found within areas of Holocene deposits. This could potentially cause damage to surface infrastructure.

6 Future changes in ground level

Comparison of the PSI velocity estimates with geoscience datasets has shown that, in the London area, the more significant changes in ground level can be attributed to the following:

1. Regional uplift (in the west) and regional subsidence (especially in the north-east and south-east)

   Regional changes in ground level can be expected to continue at similar rates over thousands of years, assuming similar conditions. Some possible consequences of climate change, such as rising sea level and increasing river volume, would tend to increase the rates of subsidence in the east of the project area, while others, such as increased rates of erosion, might serve to increase rates of uplift in the west of the area.
2. Groundwater abstraction

   Future subsidence rates related to groundwater abstraction should be in some proportion to the rates at which the aquifer is drawn down. However, when abstraction rates reach a 'steady state' within the aquifer, with no further drawdown, then subsidence can be expected to cease, probably after a time lag in the order of one to five years. Some rebound could occur following rising groundwater levels but this is likely to be less than 10 per cent of the previous subsidence.
3. Compaction of Holocene deposits

   Where no further natural sedimentation occurs, shrinkage of Holocene deposits due to compression can be expected to be effectively complete within tens to a few hundreds of years, depending on the thickness of the deposits, their composition and the superimposed load.

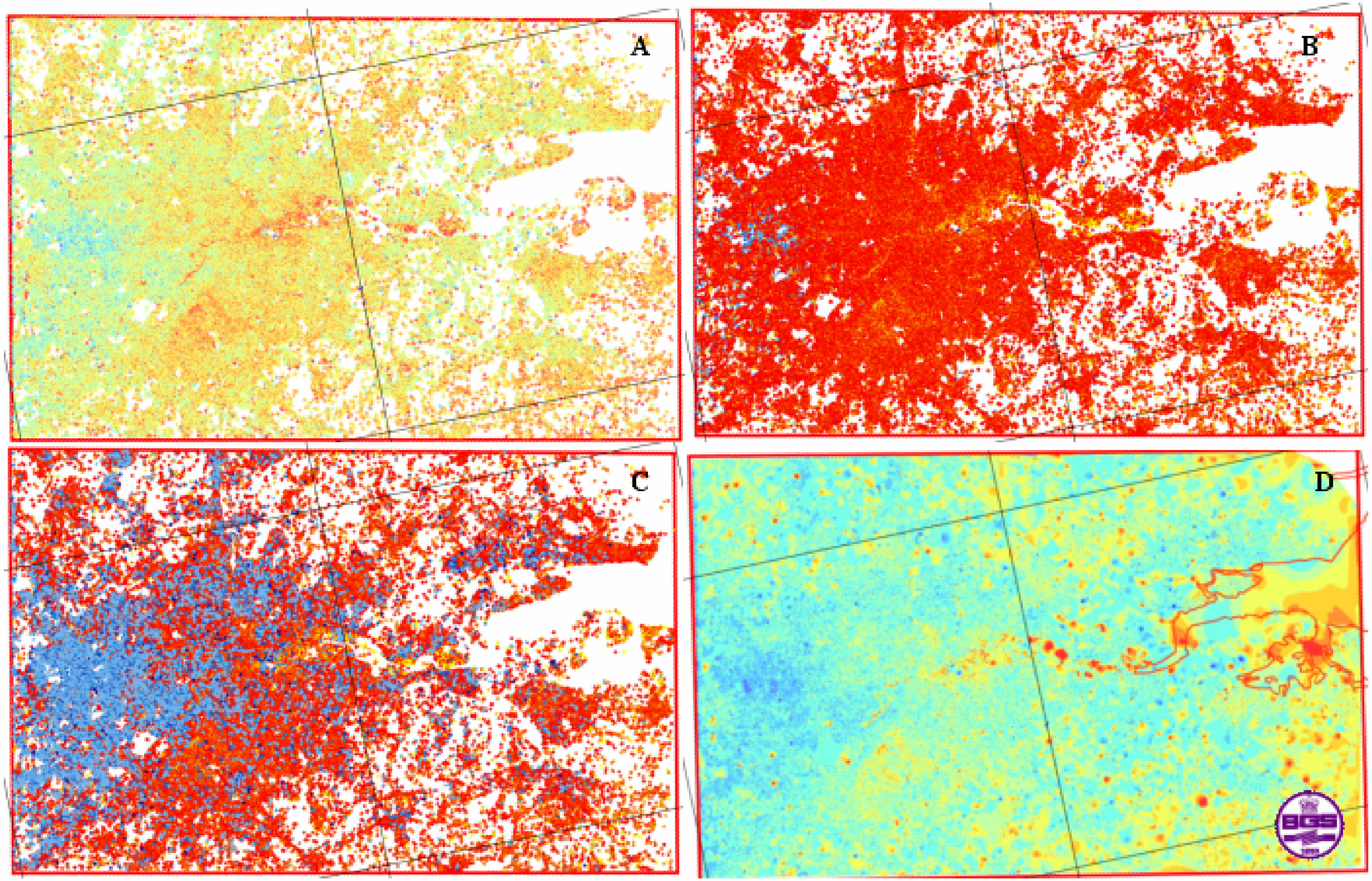
   Some areas of Holocene deposits in the London area have already been protected from flood for a significant proportion of this time scale. It can be concluded that within this century some such areas will no longer be subsiding to due to compression.

   Shrinkage due to desiccation of Holocene deposits that have been protected from flood can be expected to be effectively complete within some tens of years, depending on the prevailing weather and the level of the local water table.

   Formerly protected areas of Holocene deposits that become flooded, for example through managed retreat, can be expected to resume subsidence (or to continue to subside) due to increased loading by water and by newly deposited sediments.

4. Subsidence over tunnels

   Most such subsidence can be expected to occur within about 10 years of construction.



Scatter plots and grid derived from data provided by NPA Group, 2006

Figure 1: Graphic representations of average ground velocity values

Images have been rotated to the west by 11°; North is indicated by gridlines

A: *Scatter plot*: all average ground velocity values: colours as Figure 2

B: *Scatter plot*: average ground velocity values –1 (red) to –11(yellow) over values +1 (pale blue) to +11 (deep blue); **emphasizes subsidence**

C: *Scatter plot*: average ground velocity values +1 (pale blue) to +11 (deep blue) over values –1 (red) to –11(yellow); **emphasizes uplift**

D: *Gridded plot*: all average ground velocity values Colour shift from blue to yellow at median value

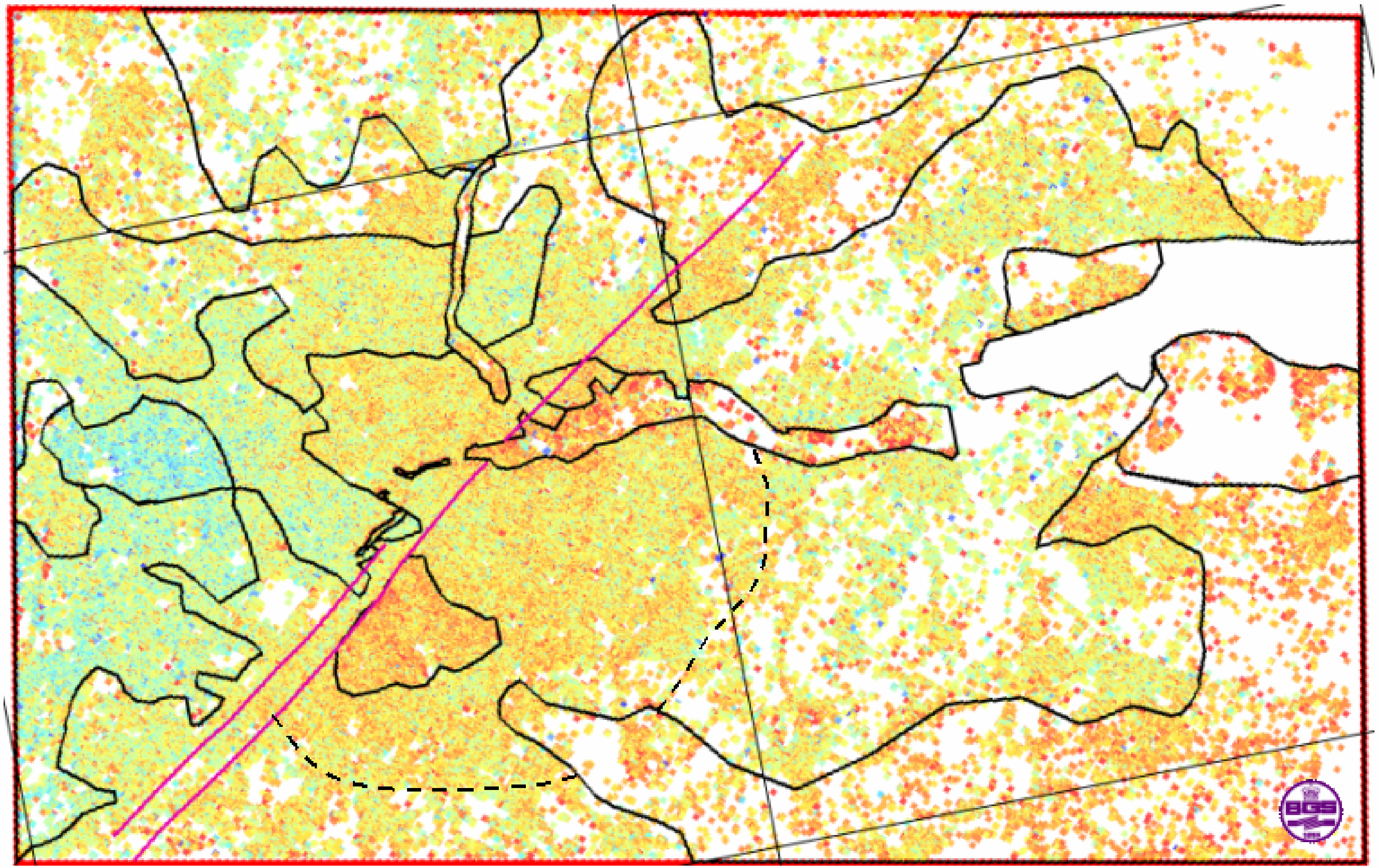


Figure 2: Average ground velocity domains and lineaments

Scatter plot derived from data provided by NPA Group, 2006

Values in mm/year

- -22 to -3
- -3 to -2
- -2 to -1.5
- -1.5 to -1
- -1 to -0.5
- -0.5 to 0
- 0 to 0.5
- 0.5 to 1
- 1 to 1.5
- 1.5 to 2
- 2 to 3
- 3 to 12

Compare Figure 3 for identity of domains. Negative values (red to yellow) indicate subsidence; positive values (blues) indicate uplift.

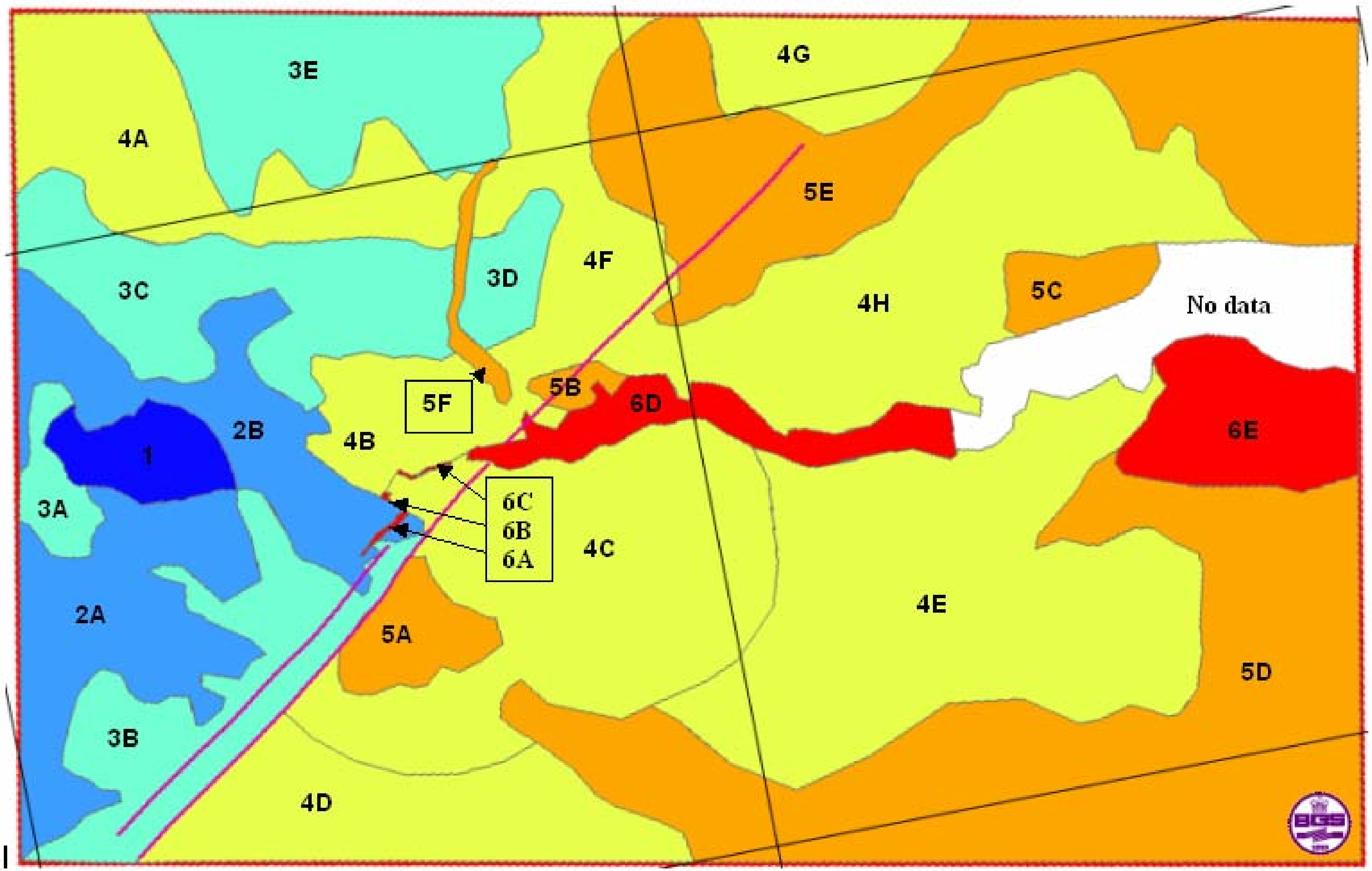


Figure 3: Average ground velocity domains

Compare Figure 2 and Table 1

Domain averages derived from data supplied by NPA Group, 2006

Domain average mm/year

1 0.5 to 0
2 0 to -0.5
3 -0.5 to -0.75
4 -0.75 to -1.1
5 -1.1 to -1.5
6 -1.5 to -2.5

Domain boundary

Lineament in distribution of average ground velocity values

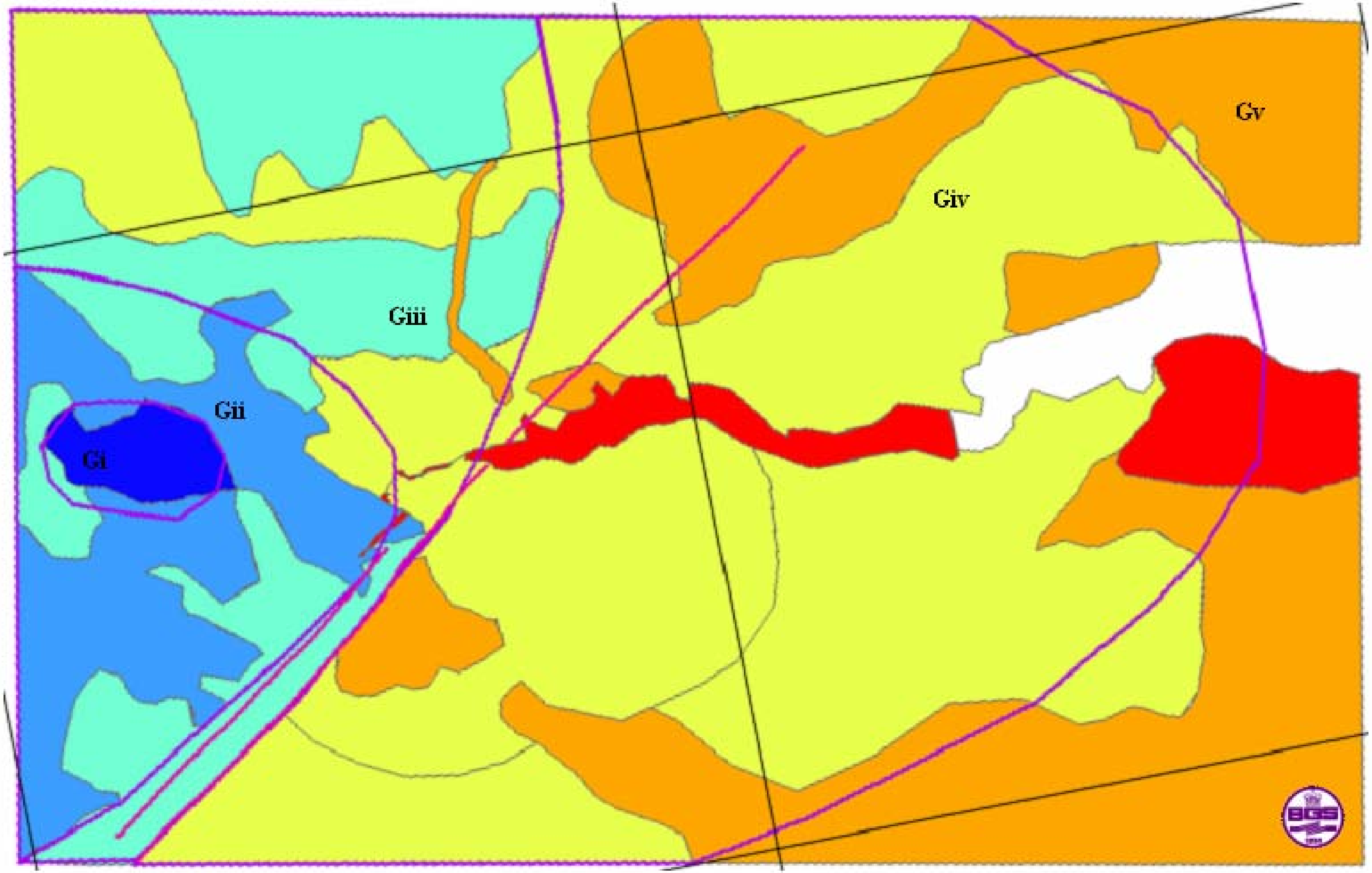


Figure 4: Generalised average ground velocity domains

Compare with Figures 1B and 1C

Scatter plot derived from data provided by NPA Group, 2006

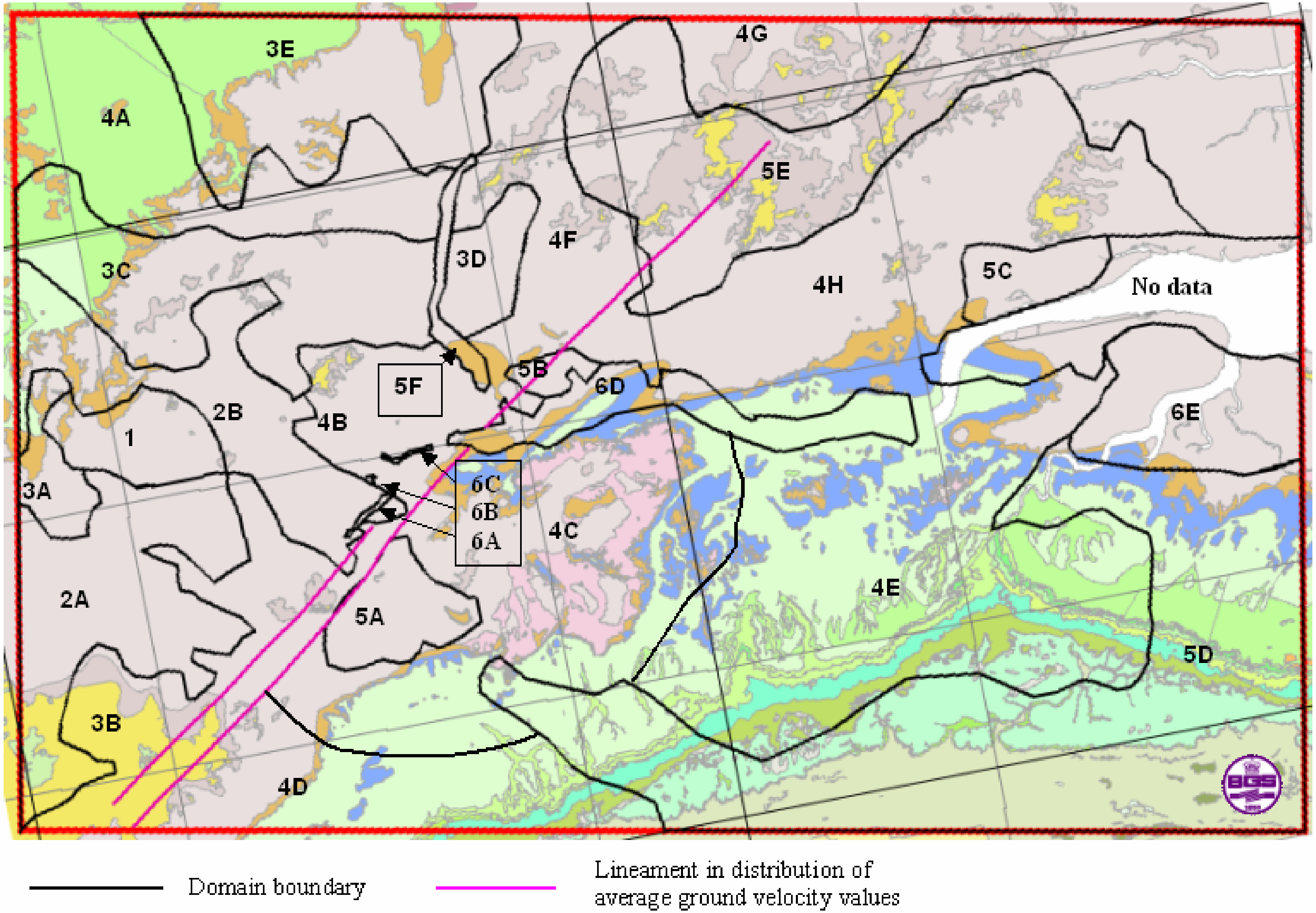


Figure 5: Average ground velocity domains on bedrock geology

Compare Figures 2 and 3

BEDROCK UNITS

- Bagshot Fmn
- London Clay
- Harwich Fmn
- Lambeth Group
- Thanet Fmn
- Chalk Group

Older bedrock units not keyed

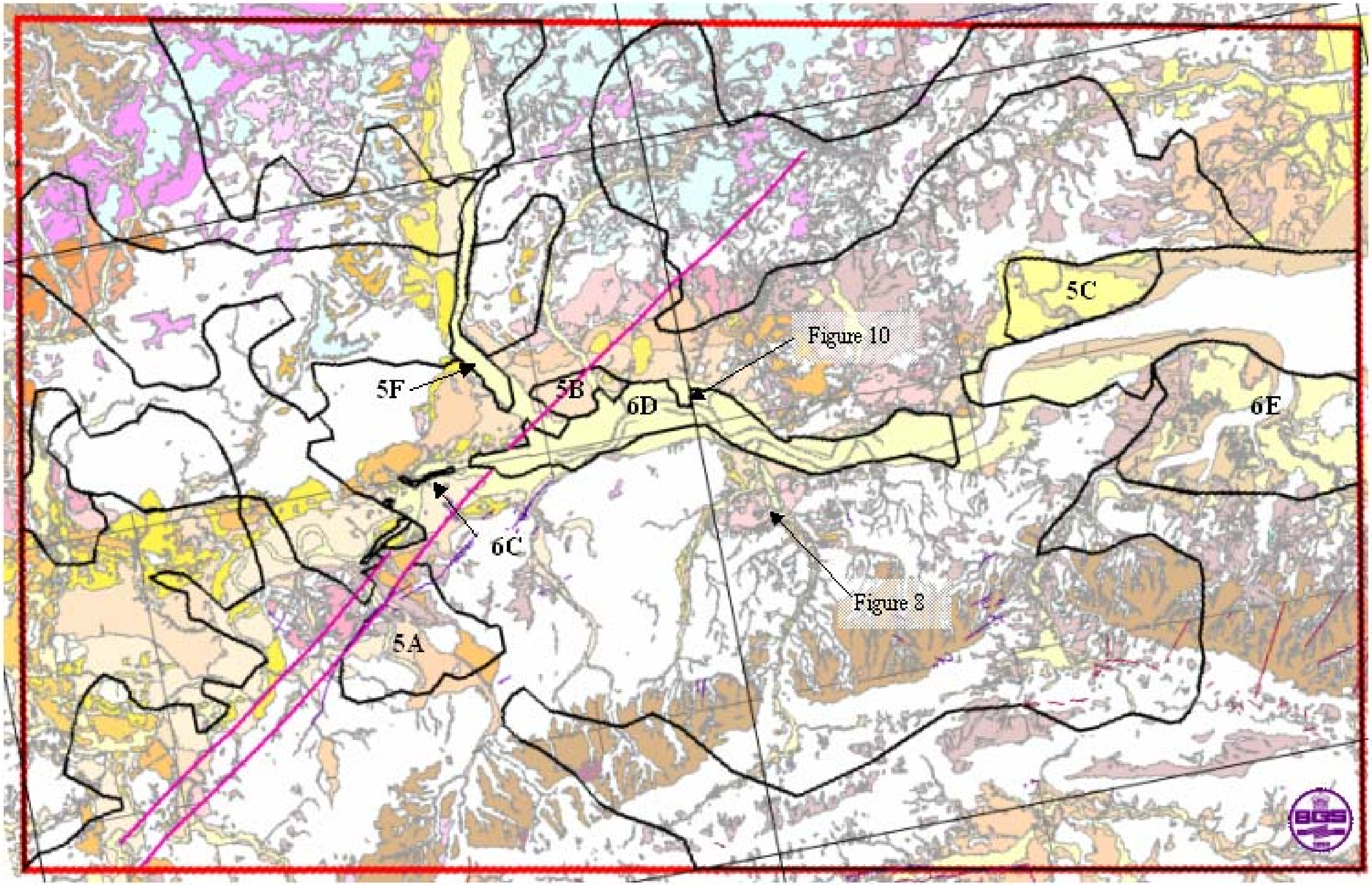


Figure 6: Average ground velocity domains and superficial deposits

Deposits of Holocene age are shown in pale yellow colours

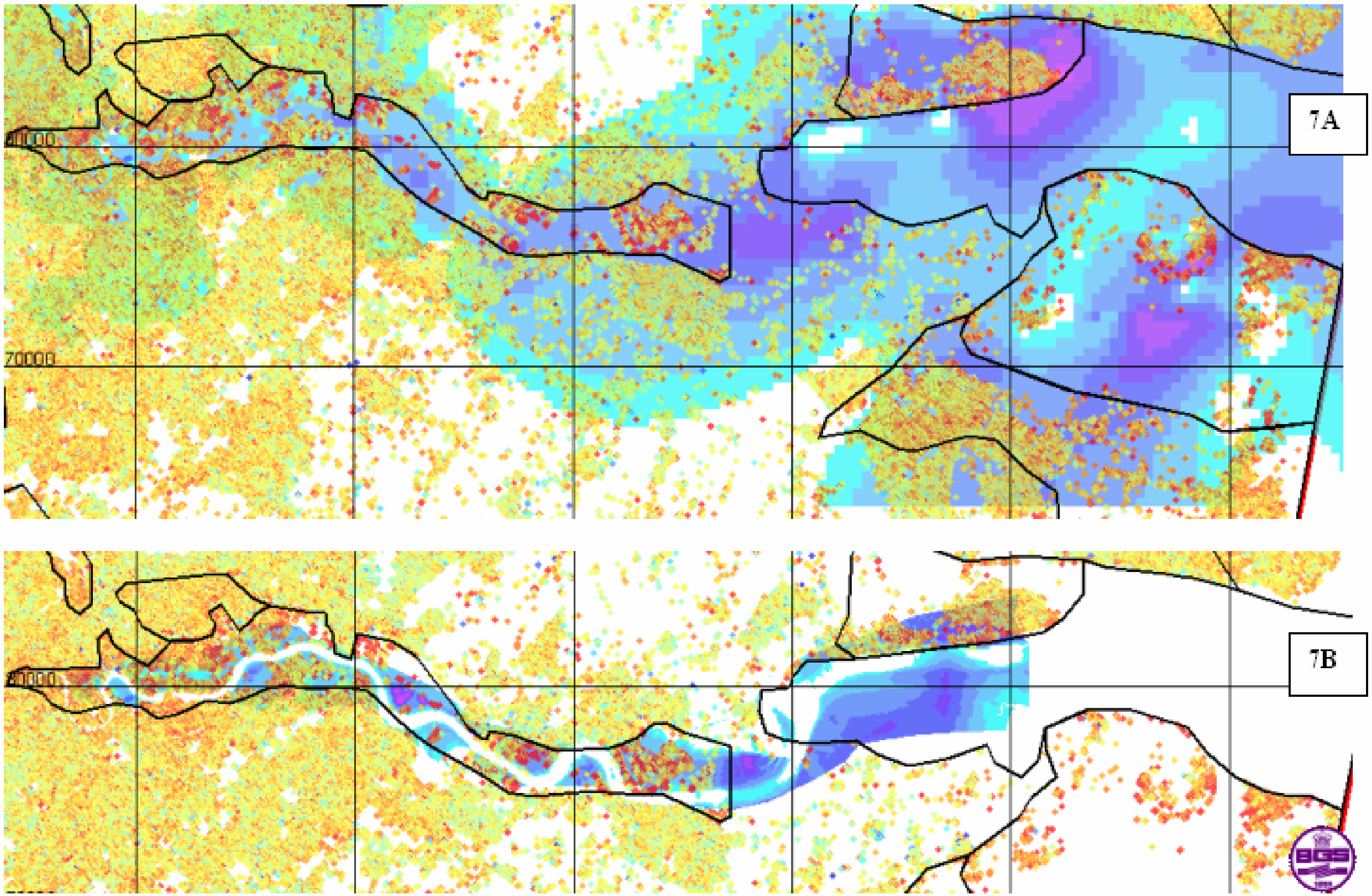


Figure 7: Average ground velocity compared with Holocene thickness

7A: 1997 model

7B: 2006 model

Velocity values and domain boundaries as in Figure 2

Scatter plot derived from data provided by NPA Group, 2006

Modelled thickness in metres

- 3 – 5
- 5 – 10
- 10 – 15
- 15 – 20
- 20 – 25
- 25 – 30
- 30 - 35
- 35 – 40

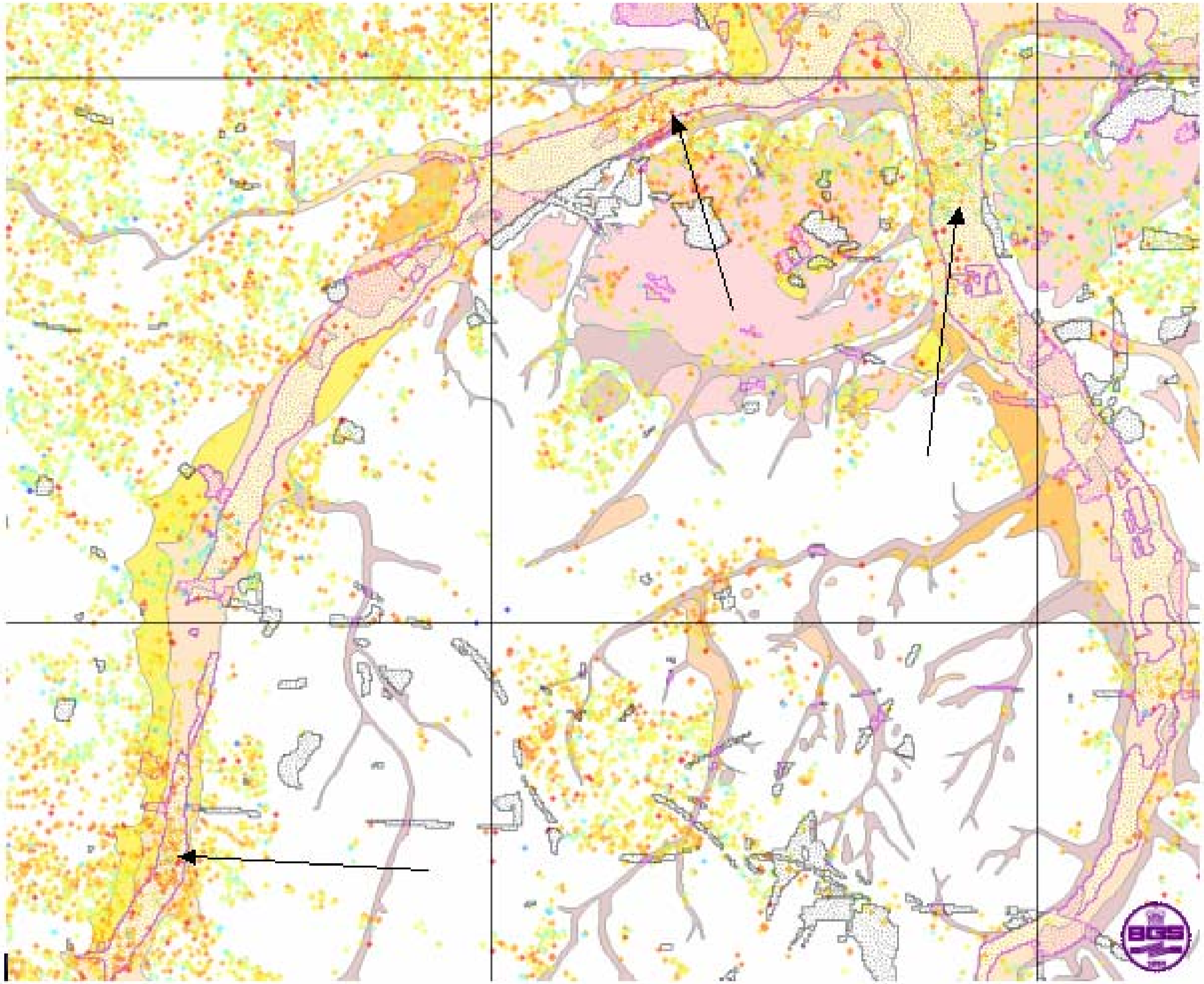


Figure 8: Detail of compressible ground map compared with average ground velocity data

For location see Figure 6.

Velocity values as in Figure 2 overlain on map of superficial deposits (plain colour) and compressible ground hazard map (stippled colour).

Magenta stipple: mostly Holocene alluvium, less than 5 m thick

Grey stipple: mostly made ground

Comparison shows that (A) many areas of compressible ground have few coincident PS points,

(B) where densely distributed PS points do occur on thin compressible ground (examples are arrowed) average velocity distribution shows little contrast with adjacent areas

Scatter plot derived from data provided by NPA Group, 2006

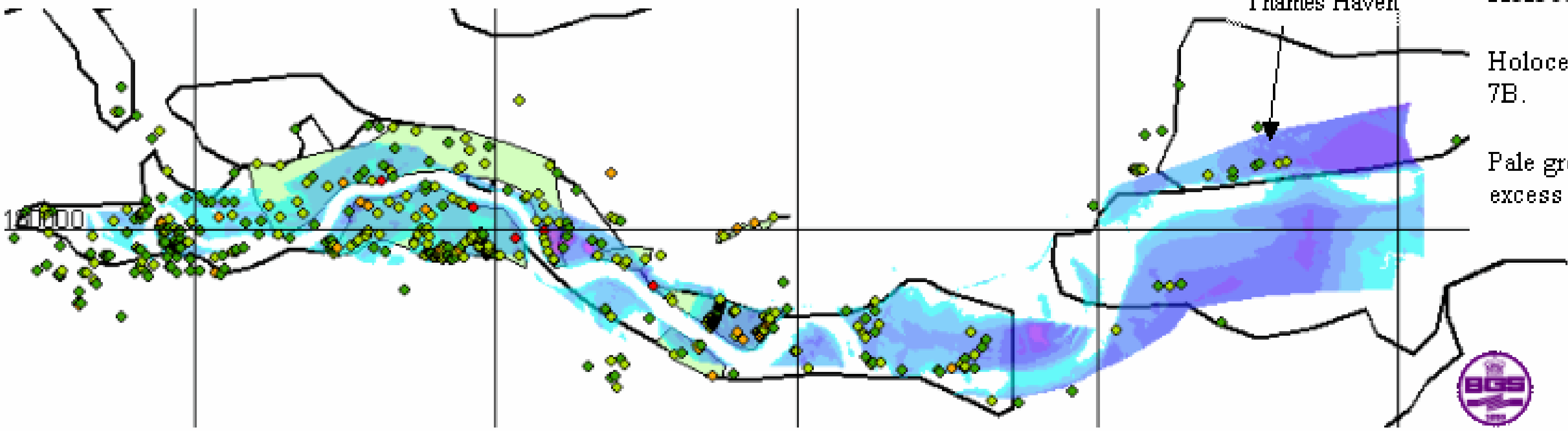


Figure 9A: Peat thickness compared with thickness of Holocene sediments

Holocene thickness as in Figure 7B.

Pale green areas have peat in excess of 2 m total thickness

- 1.1 - 2.0
- 2.1 - 4.0
- 4.1 - 6.0
- 6.1 - 8.0

Key to total peat thickness (metres)

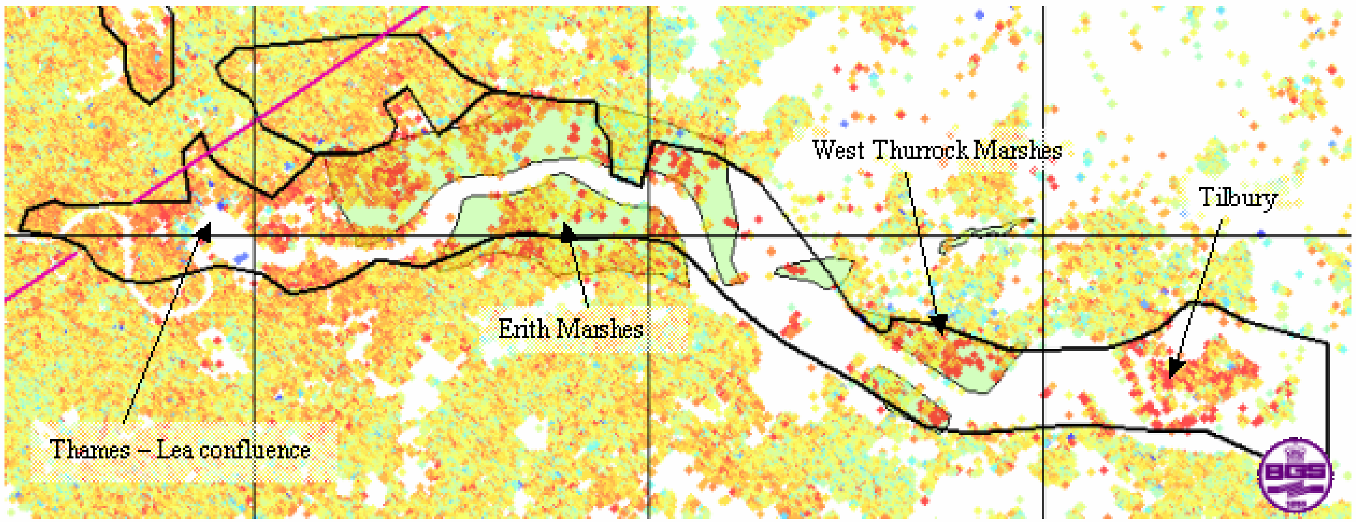


Figure 9B: Average ground velocity values and areas with thick peat

Pale green areas have peat in excess of 2 m total thickness

Velocity values as in Figure 2.

Scatter plot derived from data provided by NPA Group, 2006

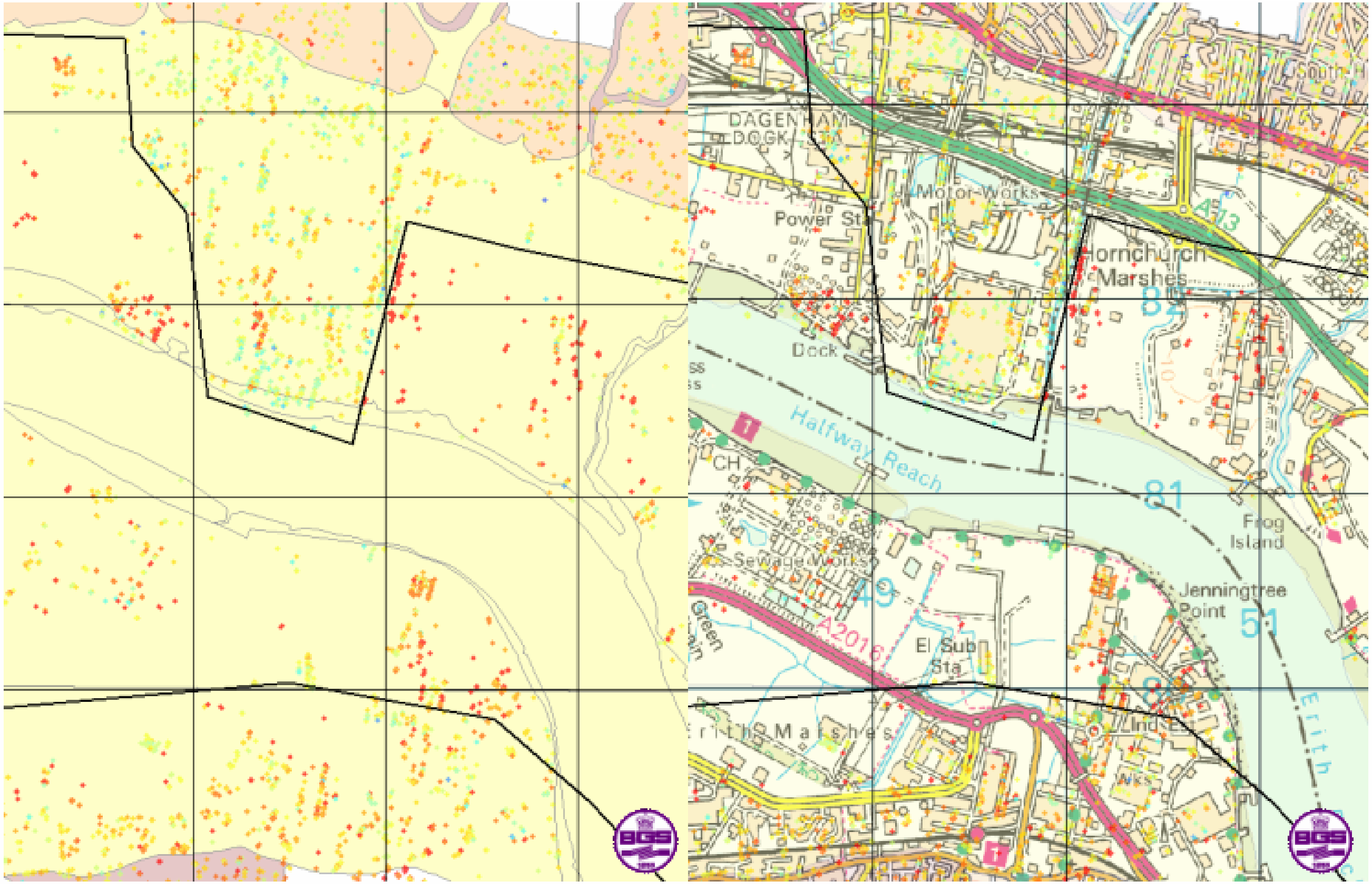


Figure 10: Anomalous areas of uplifted Holocene deposits

Velocity values and domain boundaries as in Figure 2, superimposed on portion of superficial deposits map.

For location see Figure 6.

Scatter plot derived from data provided by NPA Group, 2006

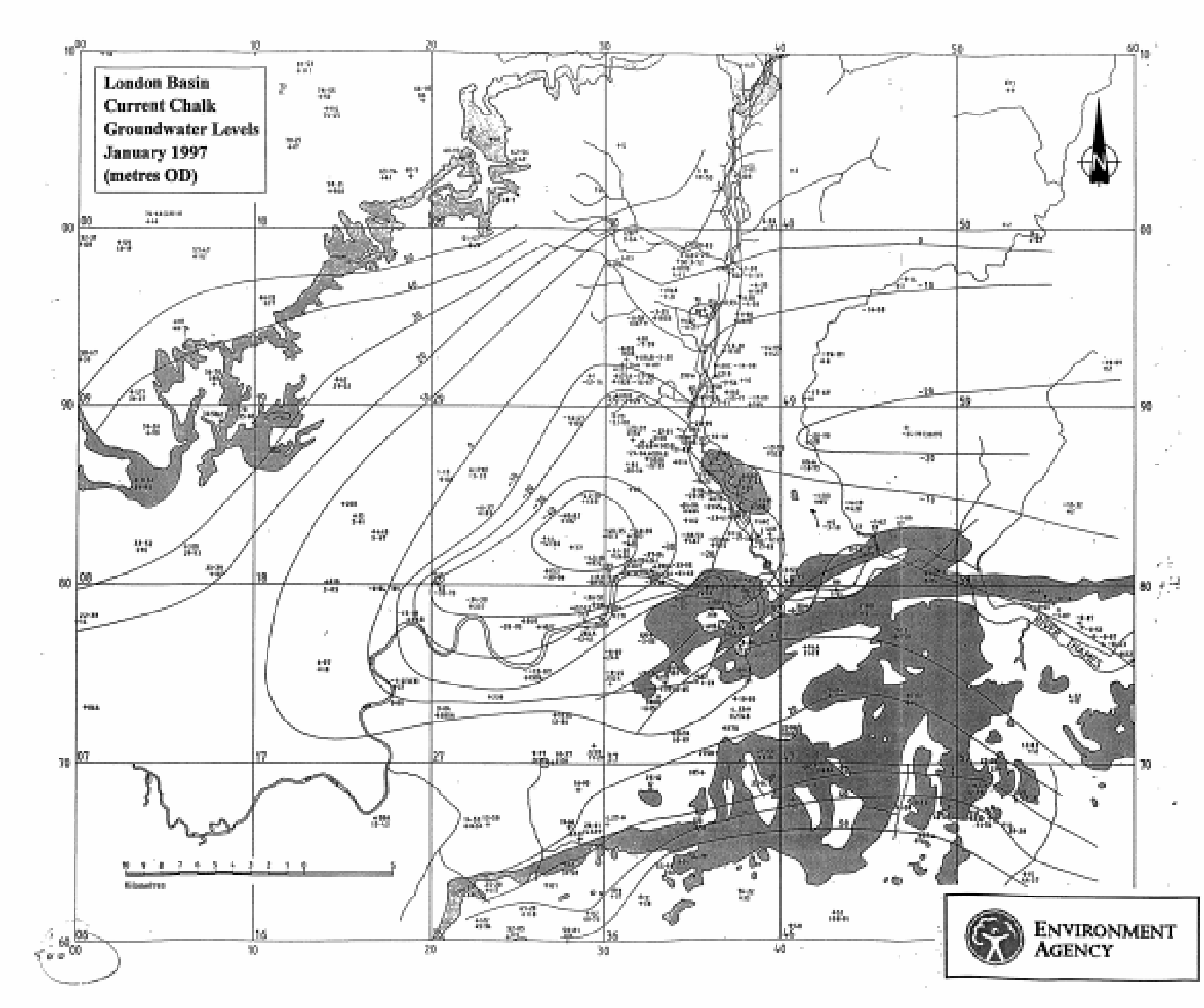


Figure 11: Example of Environment Agency groundwater level map for the London Basin: January 1997

Contours at 10 metre intervals

Dark stipple indicates outcrop of Palaeogene deposits older than the London Clay. The Chalk crops out in the areas to the north-west and south-east of the stippled areas

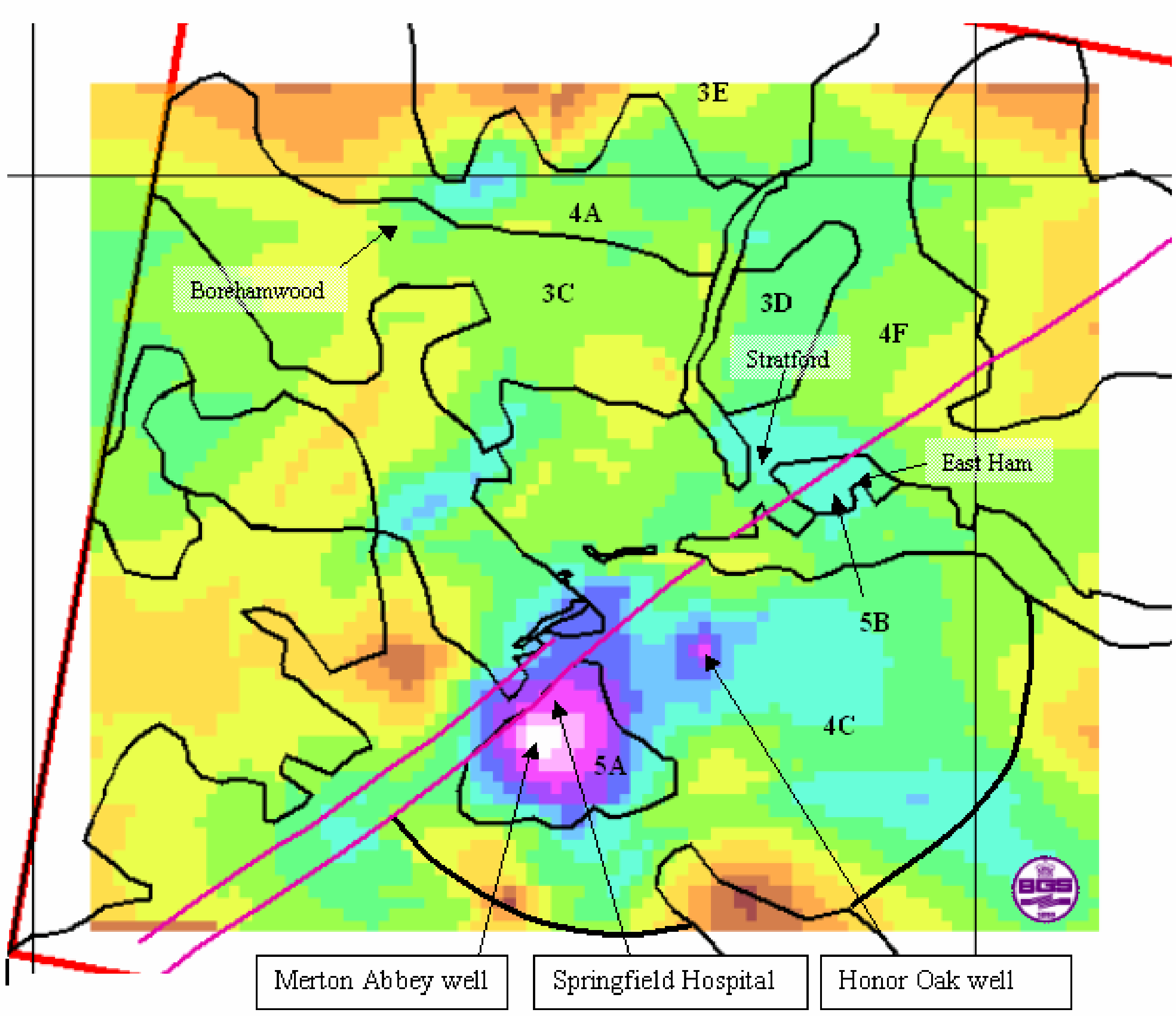


Figure 12: Change in groundwater levels in the London area, Jan 1997 to Jan 2006

Change in groundwater level during period, in metres.

Based on Environment Agency data.

Positive values represent areas where groundwater has risen, and negative values show where it has fallen

- -39.47609329 - -35
- -34.99999999 - -30
- -29.99999999 - -25
- -24.99999999 - -20
- -19.99999999 - -15
- -14.99999999 - -10
- -9.99999999 - -5
- -4.999999999 - 0
- 0 - 5
- 5.000000001 - 10
- 10.00000001 - 15
- 15.00000001 - 20
- 20.00000001 - 25
- 25.00000001 - 30

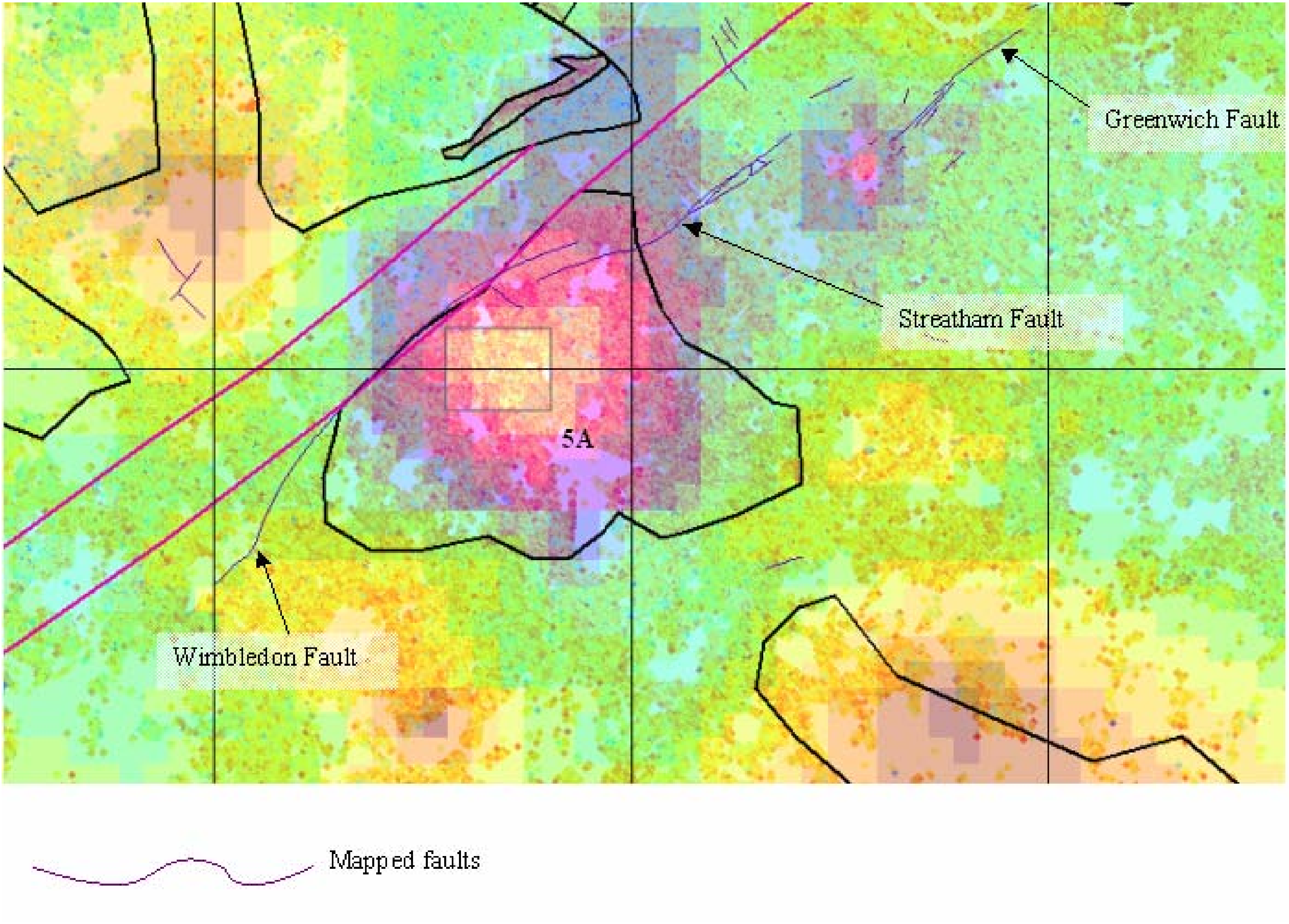


Figure 13: Detail of Figure 12, with mapped faults

Background grid based on Environment Agency data.

Scatter plot derived from data provided by NPA Group, 2006

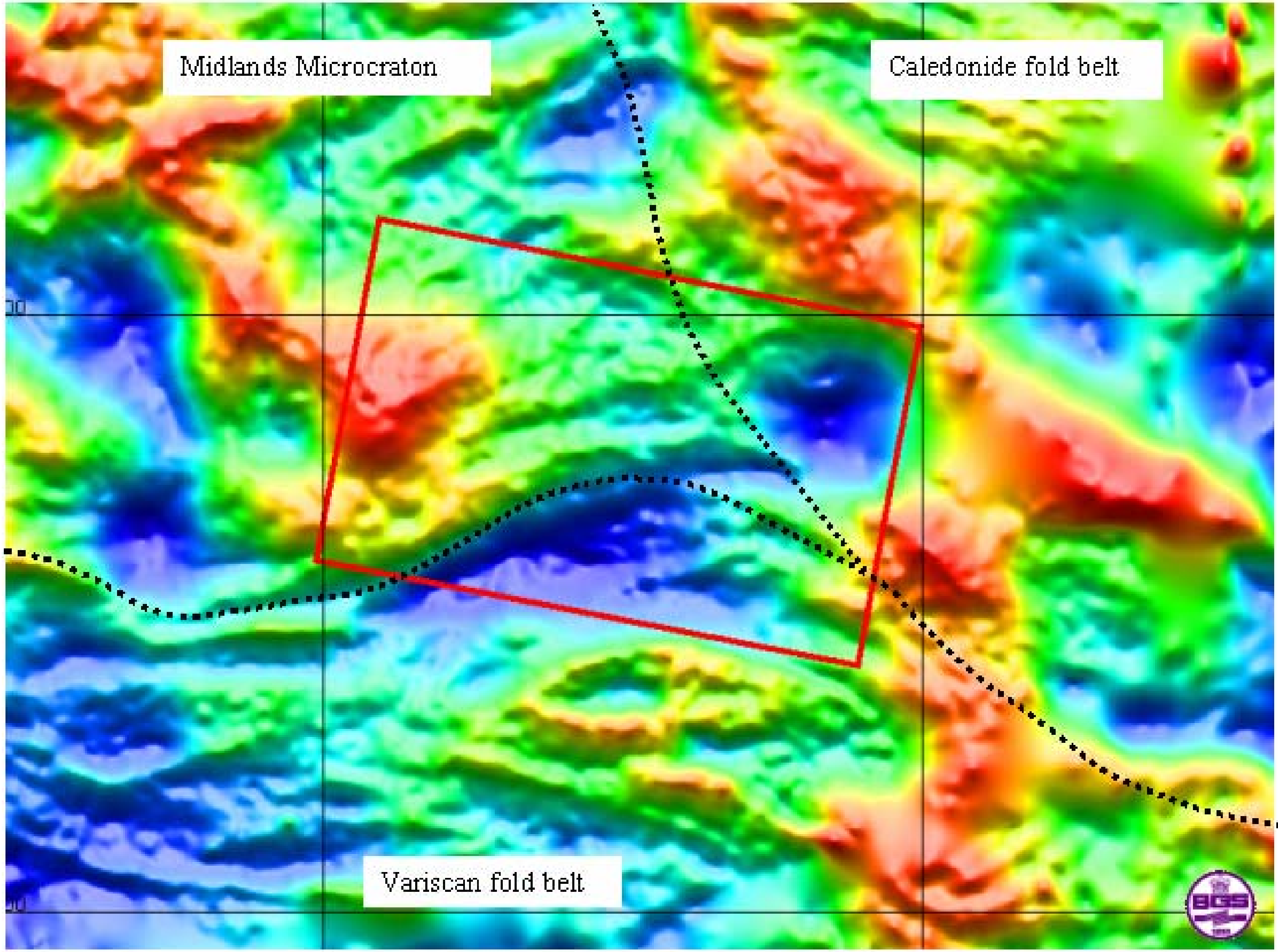


Figure 14: Project area in relation to regional gravity field

Colour shaded relief image of variable density Bouguer gravity residual of upward continued field to 10 km

Dotted lines indicate the approximate boundaries of the regional basement terranes: the 'deep geological structure'

Red: gravity 'high' (mass of underlying rock is greater than average)

Blue: gravity 'low' (mass of underlying rock is less than average)

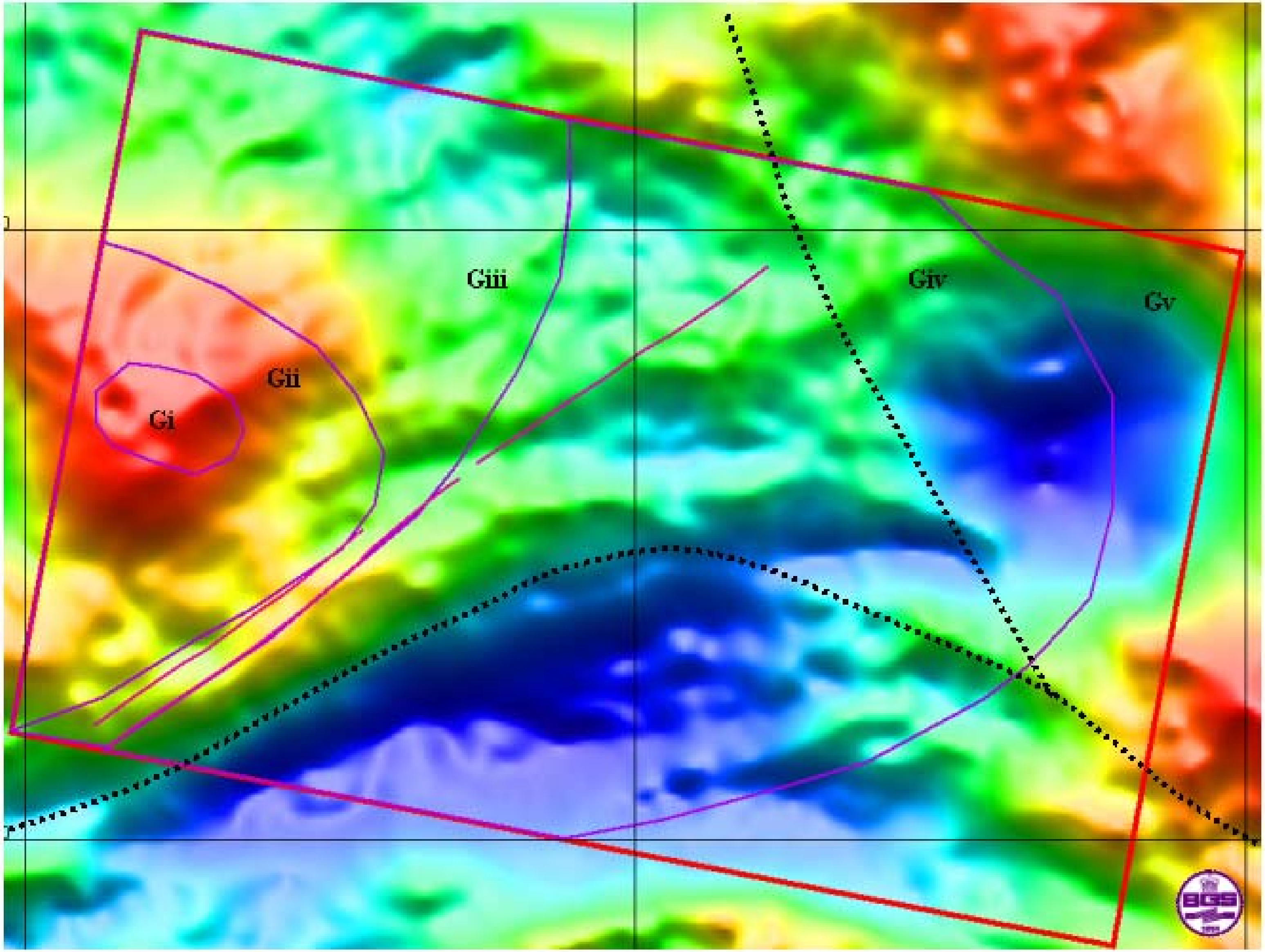


Figure 15:
Close-up of Figure 14 with generalised average velocity domains

Compare with Figure 4

Red: gravity 'high' (mass of underlying rock is greater than average)

Blue: gravity 'low' (mass of underlying rock is less than average)

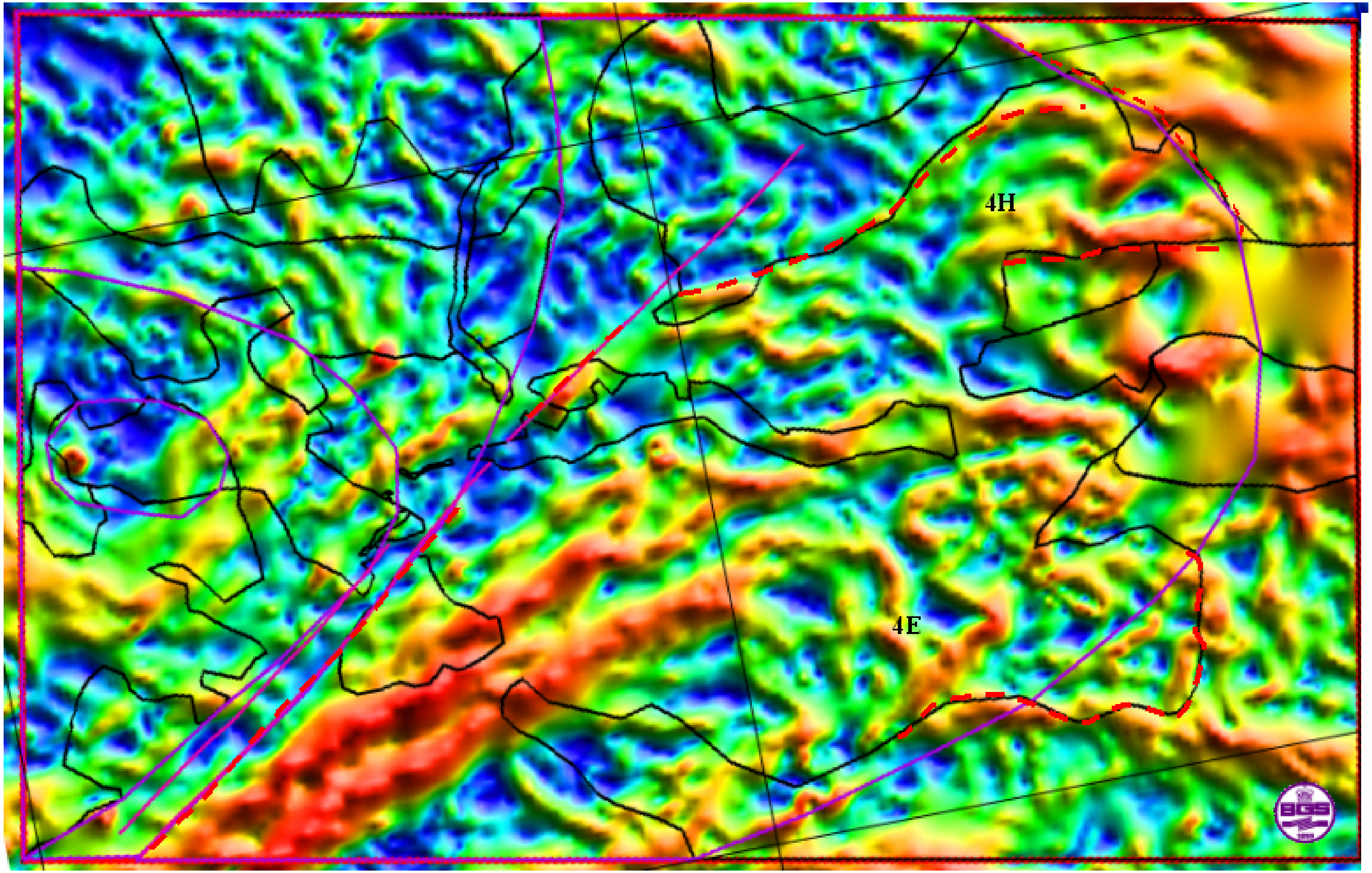


Figure 16: Regional gravity field with average ground velocity domains

Colour shaded relief image of variable density Bouguer gravity horizontal gradient

Red: rapid lateral change in gravity field

Blue: little lateral change in gravity field

Coincidence of domain boundary and geological 'basement' feature

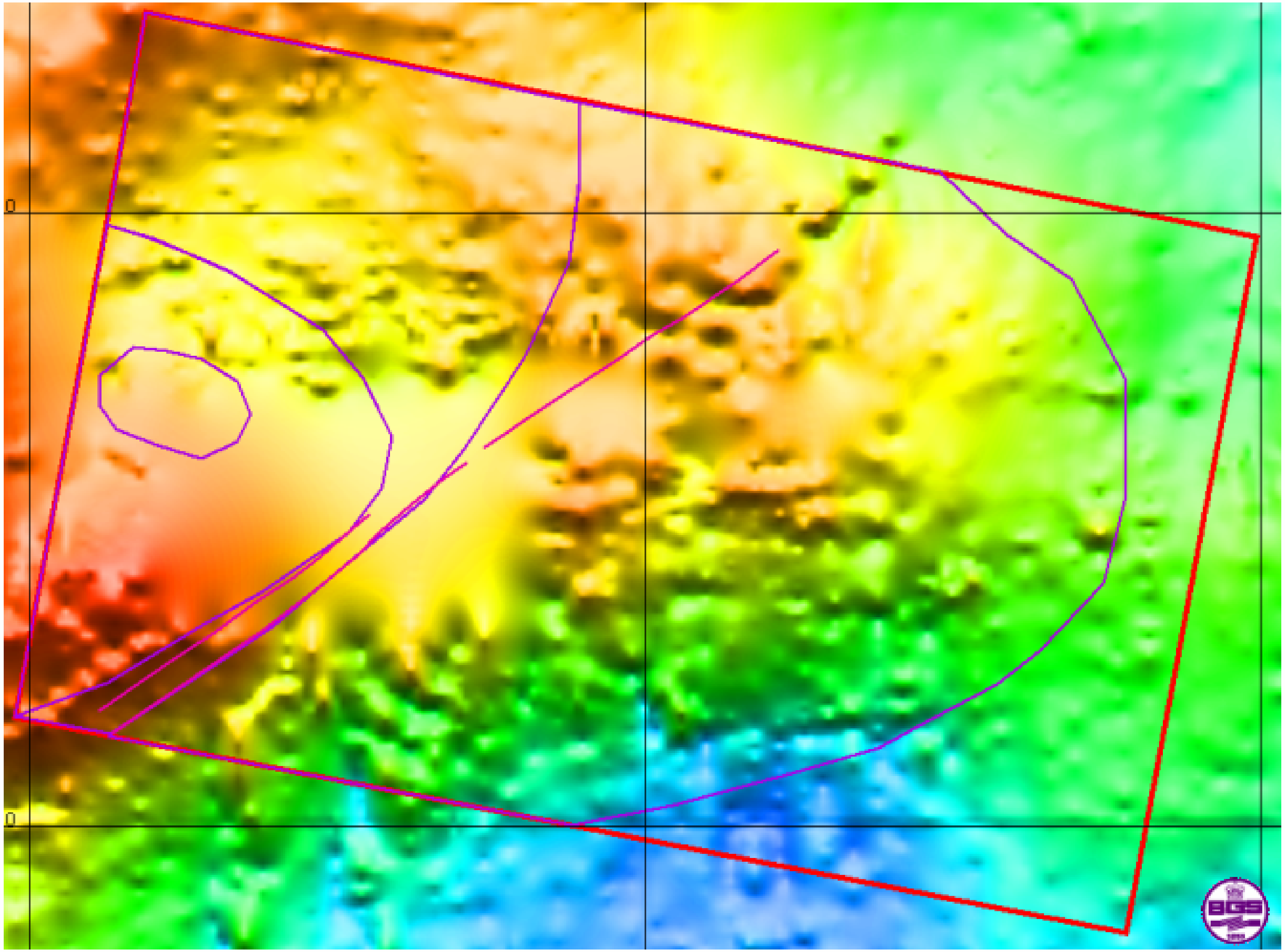
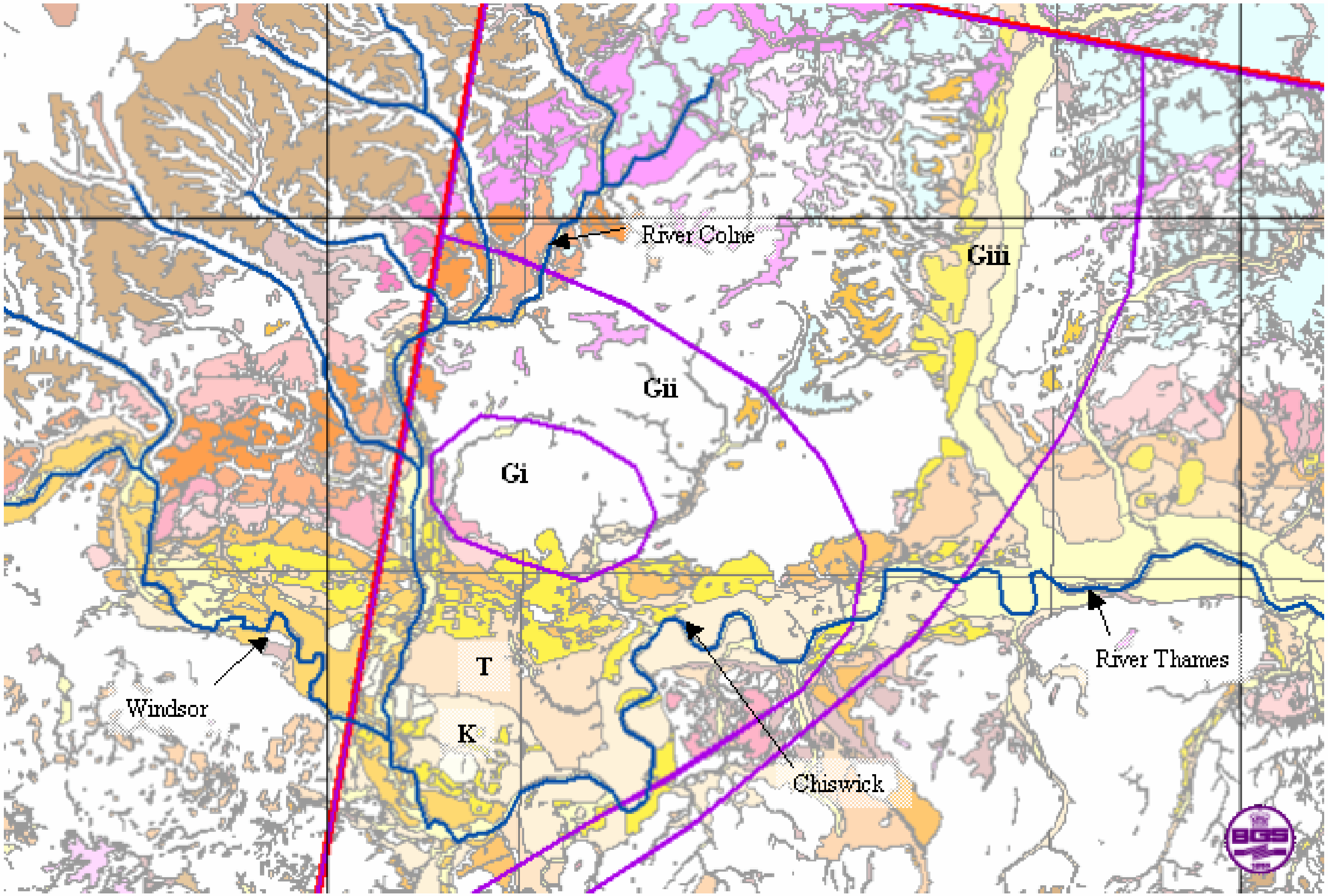


Figure 17: Aeromagnetic data with generalised average velocity domains and lineaments

Colour shaded relief image of reduced to pole field, with north illumination



K = Kempton Park Gravel T = Taplow Gravel

Figure 18: Possible river diversion around Domain Gi

Generalised average velocity domains as in Figure 4

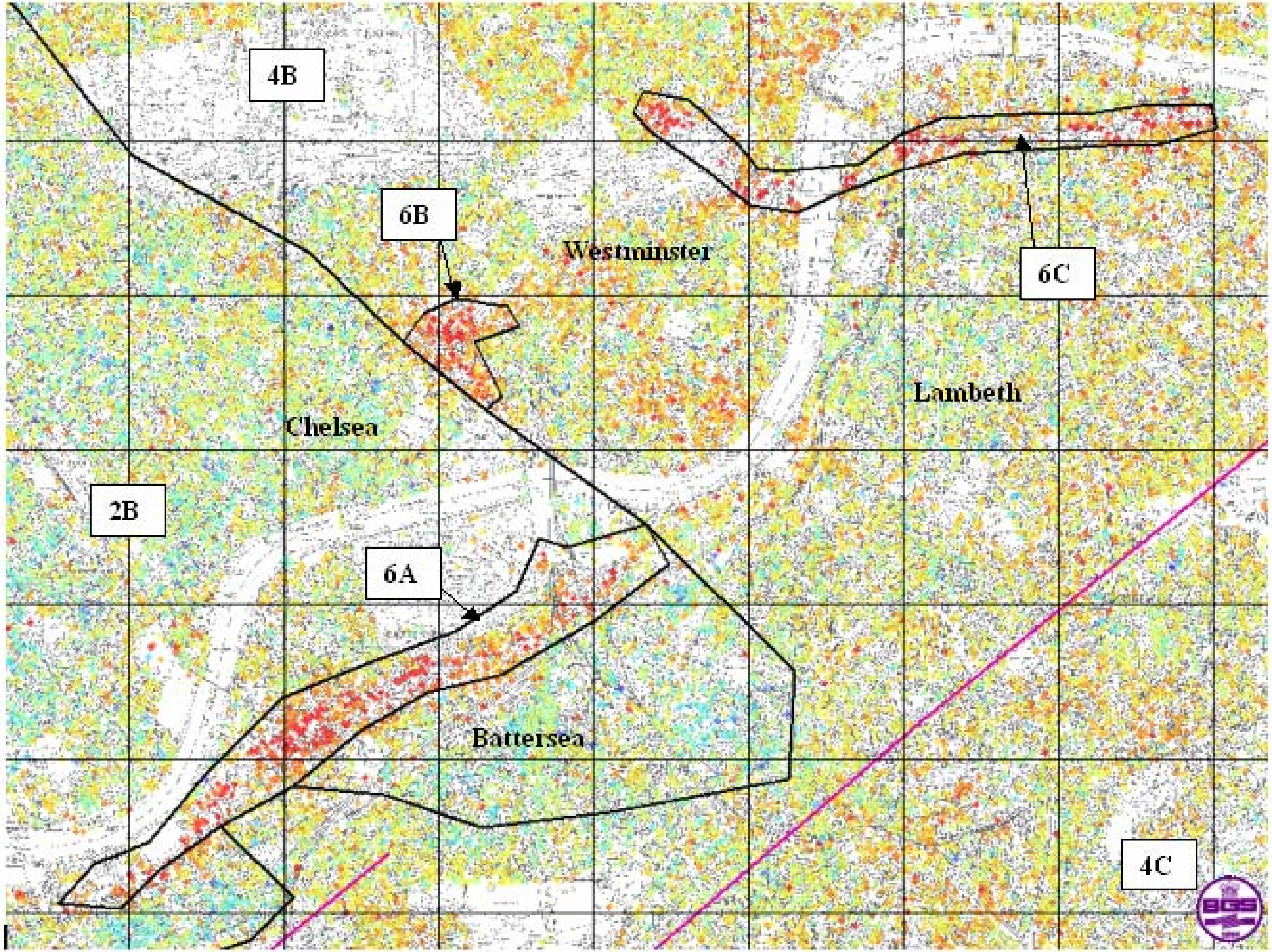


Figure 19: **Detail of average ground velocity values in south-west London**

Velocity values and domain boundaries as in Figure 2

Scatter plot derived from data provided by NPA Group, 2006

Table 1: Summary statistics for PS points within each domain

Domain	Count of PS points	Vertical ground velocity				
		Average	Minimum	Maximum	Variance	Standard Deviation
1	23632	0.34	-7.51	9.16	0.68	0.83
2A	66802	-0.11	-10.51	6.11	0.68	0.82
2B	79863	-0.34	-10.67	10.91	0.74	0.86
3A	10304	-0.55	-9.06	4.78	0.68	0.83
3B	59741	-0.61	-12.96	6.44	0.65	0.80
3C	81264	-0.68	-12.89	11.89	0.64	0.80
3D	18893	-0.53	-12.24	10.34	0.66	0.81
3E	27166	-0.59	-11.75	9.74	0.74	0.86
4A	36318	-1.02	-11.89	6.53	0.67	0.82
4B, 4F, 4H	163667	-0.86	-15.02	11.37	0.71	0.84
4C	171691	-1.06	-13.78	9.74	0.66	0.81
4D	26180	-0.98	-14.80	8.47	0.71	0.84
4E	52884	-0.86	-15.35	10.37	0.77	0.88
4G	2963	-1.04	-12.74	3.31	0.81	0.90
5A	31955	-1.55	-16.68	8.63	0.69	0.83
5B	6271	-1.18	-6.45	3.85	0.71	0.84
5C	5441	-1.31	-10.75	3.35	1.15	1.07
5D	34844	-1.49	-20.59	4.52	0.83	0.91
5E	28991	-1.23	-10.34	8.61	0.69	0.83
5F	3398	-1.30	-5.59	5.27	0.91	0.95
6A	1066	-2.06	-6.93	2.50	1.79	1.34
6B	272	-2.43	-5.10	-0.22	0.76	0.87
6C	655	-2.25	-9.33	1.27	2.44	1.56
6D	14090	-1.99	-22.34	6.58	3.49	1.87
6E	3322	-2.05	-15.23	4.34	2.68	1.64

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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